L	P	I	M	C		

(1) Date of Storm: 1967

(2) Exact location of observed hail occurrence: ...... 1/4 S..... T..... R..... W of .....Meridian

(3) Hail began at ....AM or at ....PM ; Hail lasted for ....minutes.

(4) During this time: it never stopped hailing ☐ ; OR there were ☐ bursts of hail; OR there were an unknown number of bursts ☐ .

(5) Size of largest hail: shot ☐ pea ☐ grape ☐ walnut ☐ golfball ☐ larger ☐
Size of most common hail: shot ☐ pea ☐ grape ☐ walnut ☐ golfball ☐ larger ☐ .

(6) Average spacing of hailstones on the ground at end of storm was ....inches.
OR if ground covered, depth of hail was ....inches.

(7) Hail began: before rain ☐ ; at same time ☐ ; after rain began ☐ ; OR no rain ☐ .

(8) Largest hail fell: at beginning ☐ ; in middle ☐ ; towards the end ☐ ; throughout storm ☐ .

(9) Was any hail soft or slushy? yes ☐ no ☐: if yes estimated largest size ....

(10) Were any hailstones irregular or non-spherical in shape? none ☐; a few ☐ ; about half ☐; OR most ☐

(11) On what other property do you know it hailed? ..... 1/4 S..... T..... R..... W.....

(12) Remarks:

Name .... Address ....

If you need more cards, check here ☐ Phone .... Exchange ....

THE UNIVERSITY OF ALBERTA

SPATIAL AND TEMPORAL ANALYSIS OF HAILFALL OCCURRENCE IN CENTRAL ALBERTA

by

(C) ALEXANDER PAUL

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

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FACULTY OF GRADUATE STUDIES

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "Spatial And Temporal Analysis of Hail Occurrence in Central Alberta", submitted by Alexander Paul in partial fulfilment of the requirements for the degree of Master of Science.

ABSTRACT

The Alberta Hail Studies project has placed the data from every hail report received from its co-operative observer network on to an IBM card. Some thirty thousand of these cards, covering the ten summers 1957-66, form the basis for the climatological study of certain Central Alberta hail patterns which is conducted in this thesis. Use is also made of the project log books and summaries, which record all hail reports received and the sizes of the largest stones observed.

The frequency of a hail day rises sharply from late May to a peak in late June, when the probability of a hail day is 0.8. The hail day frequency falls off gradually through July and August, and then more rapidly, with the season effectively over by mid-September. There is a strong tendency for persistence, with hail days occurring in runs. There is also some evidence of singularities, correlating more closely with those in Switzerland than in either Illinois or the Denver area.

Spatial and temporal variations of hail frequency, time of onset, hailfall duration and maximum observed hail size are presented. The data are also stratified into five-mile wide strips running parallel to the main divide of the Rocky Mountains.

A hail frequency index valid for regional comparisons in Central Alberta is derived. Its spatial distribution is plotted and variation with distance from the Rockies is also examined. The frequency is highest close to the mountains and decreases with increasing distance.

Mean hail onset time varies from year to year and during the season. Forty miles from the Continental Divide mean onset is 1500 MST; it becomes

progressively later with increasing distance, occurring at 1730 MST two hundred miles away. In addition to the main period of afternoon activity, there are secondary periods in the morning and late at night at various distances from the divide. Finally, the diurnal distribution of hail onset times is related to the maximum size of the hail produced.

Mean hailfall duration varies rather haphazardly from year to year and through the hail season. The overall mean is ten minutes. Spatial analysis shows an average of thirteen minutes close to the mountains, decreasing to only eight minutes two hundred miles away. A small area of 250 square miles just east of the city of Calgary has a mean duration of longer than twenty minutes, and 15 per cent of the recorded falls were in excess of twenty-five minutes.

Large hail (long axis greater than or equal to 2 cm.) occurs in 18 per cent of all reports, on the average. However, this ratio varies considerably. In a temporal frame, it has a maximum in August. Spatially, the greatest frequency of large hail (39 per cent) coincides with the area of longest hail durations just east of Calgary. Twenty-six per cent of the observations in the strip eighty miles from the divide have reported maximum hail size greater than or equal to 2 cm. There is no decrease with distance from the Rockies but rather a series of fluctuations. These correlate to some extent with those shown by mean duration and hail frequency, suggesting that wave motions produced in the troposphere by the Rocky Mountains may have some significance.

Comparative studies of world hail climatology showed that the hailstorms of Colorado are the most similar to those of Central Alberta in terms of the hailfall patterns they produce. Certain inferences are drawn concerning a hailstorm model for the area, and suggestions made for further research which could help in clarifying this picture.

ACKNOWLEDGEMENTS

During the summer of 1966, I was employed as a summer assistant by the Research Council of Alberta on its Alberta Hail Studies project, located at Penhold, near Red Deer. The material presented in this thesis results from an analysis of the basic hailfall data collected by the project. This analysis was performed, with financial assistance from both the Research Council of Alberta and the Department of Geography, University of Alberta, Edmonton, in the winter of 1966-67.

The lengthy computer programming needed was undertaken by Mrs. M. Easton of the Department of Computing Science at the University of Alberta. Without her invaluable assistance this thesis would not have been possible. I am also grateful to the Department of Computing Science for the use of the computer and their many and varied services.

Data from the Hail Studies project were made readily available to me. I am indebted to the Research Council of Alberta both for financial support and the use of their facilities. Discussions with the Hail Studies staff were very fruitful in providing suggestions and ideas. In particular I would like to thank Mr. Ford Bergwall, Mr. Michael Balshaw of McGill University, and of course my supervisor, Dr. Peter Summers, the head of the Alberta Hail Studies field programme, for his constant interest, watchful eye and constructive criticism. Dr. R.H. Douglas, of the Department of Agricultural Physics, Macdonald College, Quebec, was very kind to locate and send me the data I required which were stored in Eastern Canada. I am also grateful to Mr. Philip S. Brown of the Crop-Hail Insurance Actuarial Association, Chicago, for the selection of research reports he was good enough to send me.

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INTRODUCTION

The Alberta Hail Studies project has been in operation since 1956. It maintains a storm-detection radar at Penhold in Central Alberta, undertakes time-lapse cloud photography and keeps up various meteorological recording instruments set out over Central Alberta. But the basis of the hail observations is a volunteer network of farmers reporting hail occurrences by mail on business-reply postcards. During the last several years, the farmer reports have been augmented by the efforts of the Hail Studies personnel in surveys of individual storms to produce additional report coverage.

Information and report cards are mailed out to some 25,000 farmers at the beginning of the hail season, which lasts essentially from mid-May to mid-September in Central Alberta. Of all these potential observers, only a relatively small percentage sends in reports. It seems that the response for a given storm is at least partially correlated with its severity; hence the number of mailed-in reports for any one hail day can be regarded as an approximate indicator of the activity on that day. Where individual storms are of special interest (for example, those well-documented by radar and/or cloud photography), the survey technique may be invoked to furnish additional information. This takes the form of establishing contact with the farmer by car or by telephone, thus soliciting reports from observers who would otherwise not have reported.

There are, of course, shortcomings in the material obtained. The format of the report card has changed over the years. Increasing experience in handling and analysing the data received has led to a gradual evolution in the questions asked, and allowed more and more useful information to be derived from the farmers. Only certain of the more basic questions have

been asked during the whole ten-year period. Variations in population density across the project area mean that hail observations are more plentiful in some parts than in others. One hail report per township in the foothills does not necessarily mean a less severe storm than ten reports per township in the Lacombe area.

Even so, there are many Hail Studies data that will bear useful analysis. Details of the time and geographical location of the reported hail have been obtained throughout the entire period of project operations, together with the maximum sizes of stones observed. Ten years of data seem a reasonable base for the performance of a climatological analysis of the spatial and temporal variations shown by some of the characteristics of Central Alberta hail. Other data have been collected over somewhat shorter periods of time, but it is proposed that some of these be investigated here also.

The project area (Figure 1) is limited by the effective range of the radar, about ninety miles. It extends to Leduc in the north and to High River in the south, and in the west fades into the unpopulated region of the Rocky Mountain foothills. A north-south line through Castor and Hanna marks the eastern boundary. Some indication of the local topography is given in Figure 1, while Figure 1a shows many of the tracks followed by hailstorms in past seasons.

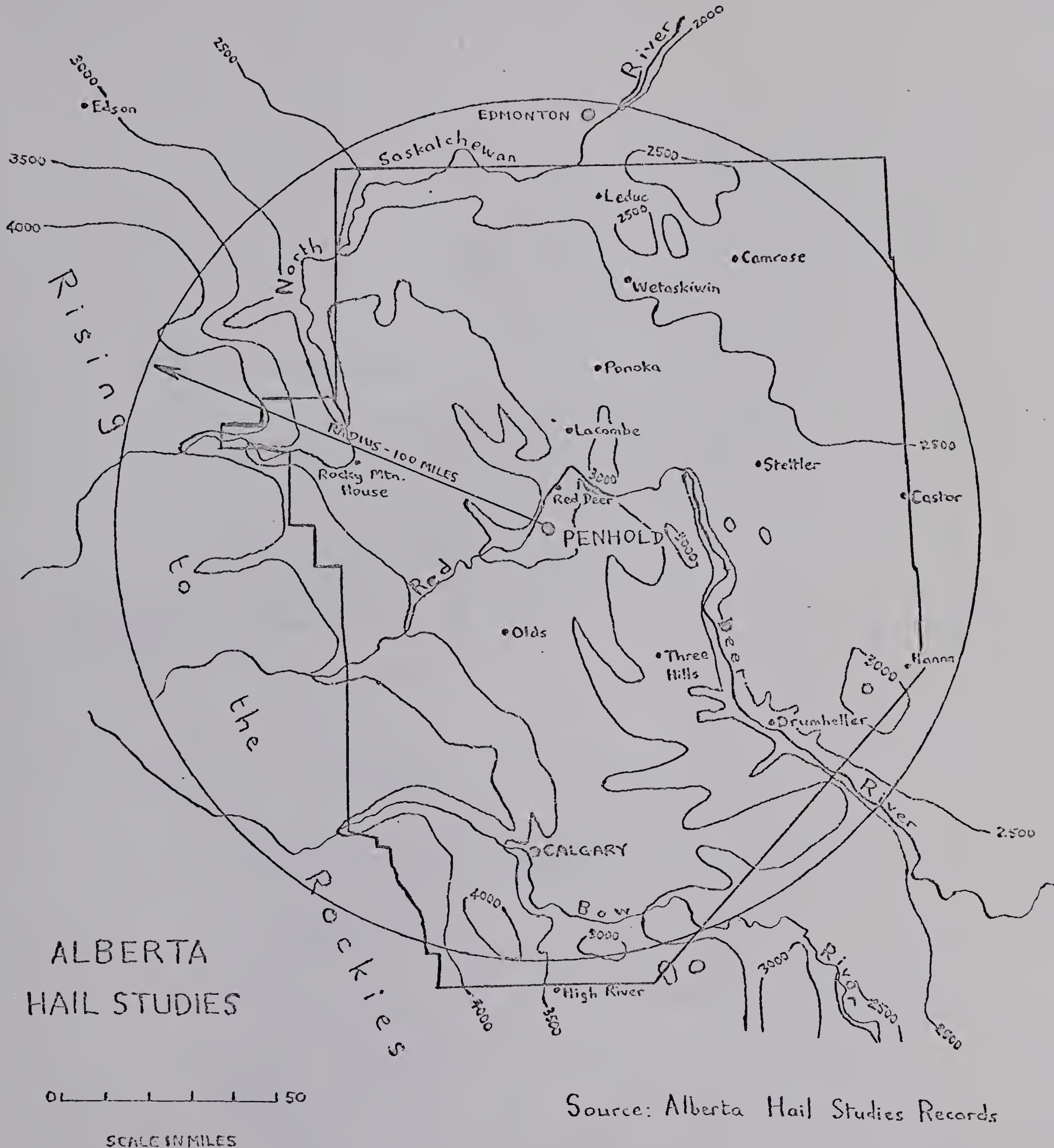
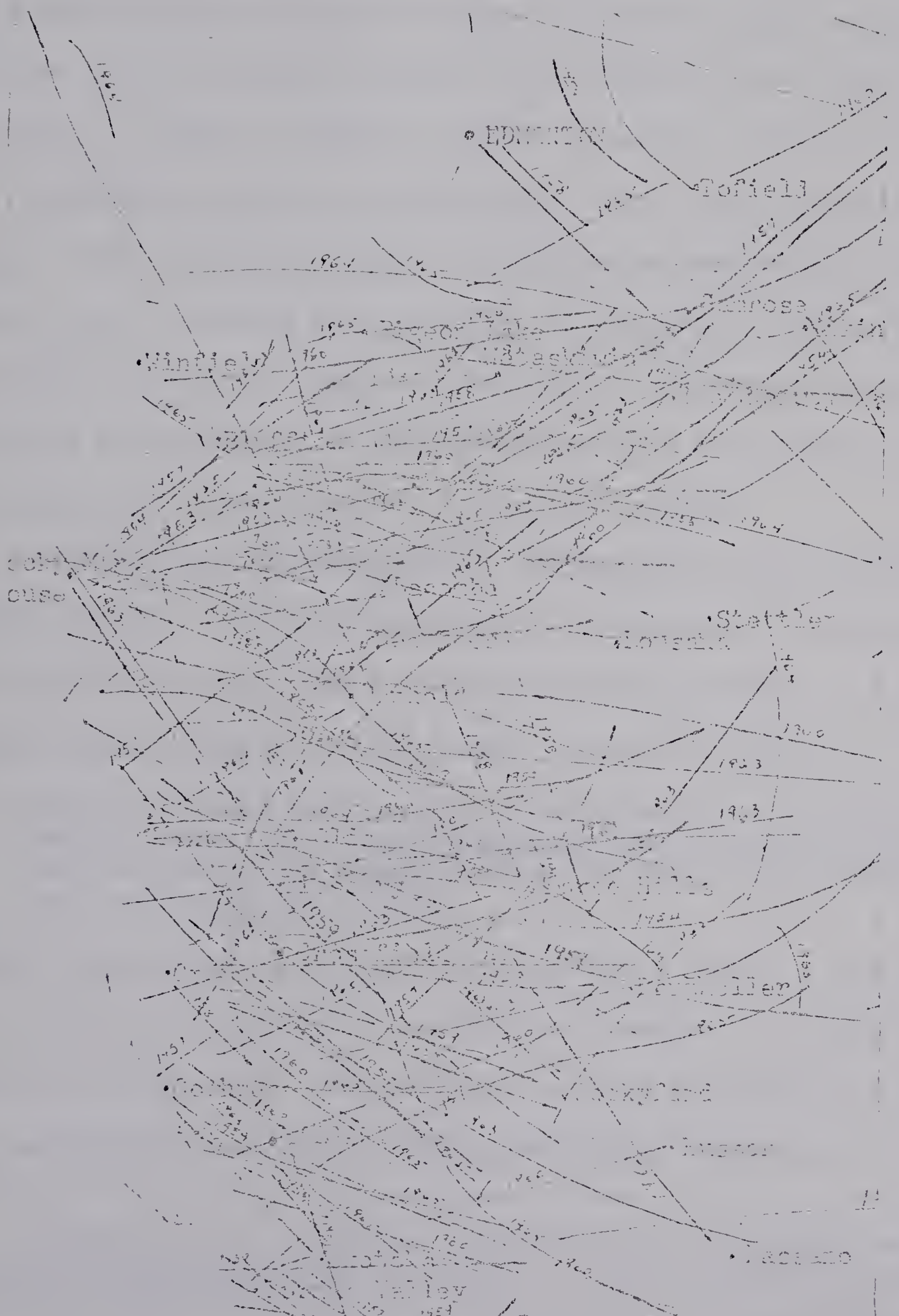


Figure 1 - The Project Area



After Thompson

FIGURE 1a - HAILSTORM TRACKS IN CENTRAL ALBERTA, 1954 AND 1957-65

CHAPTER I

WORLD HAIL CLIMATOLOGY

Hail climatology has received greatest attention in those parts of the world where hailfall is quite frequent. Reports of hail occurrence are obtained from all kinds of sources, for it tends to be a fairly localised phenomenon. Indeed, a synoptic network of weather observing stations may be too scattered to give any real indication of the hail patterns in a given region.[1] Official meteorological records can be supplemented by newspaper reports, and by delving into the files of the various hail insurance boards throughout the world. There are also several individual projects pursuing intensive investigations of hail occurrence in a particular area, based on the reports of a dense network of voluntary observers.

Hailfall, which is mentioned in the Bible,[2] is often a spectacular and damaging feature. An early reference to a storm of A.D. 1246 testifies to this. Carpini, a papal legate to the court of the Mongols at Karakorum, two hundred miles southwest of Lake Baikal, writes of August 15:

> "While the friars were present at the election of the Khan or Emperor, hail fell in such quantities that more than 160 men were drowned by its sudden melting, and their property and huts were swept far away."[3]

Besides the millions of dollars in crop losses suffered by agriculture each year, hail also causes injury to livestock, damage to buildings and property, and loss of human life. Flora mentions a storm in India which claimed more than two hundred lives,[4] while Sansom reports an authenticated case of death

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[1] Beckwith, W.B., "Analysis of Hailstorms in the Denver Network, 1949-58", in Physics of Precipitation, Weickmann, H. (ed.), Baltimore, Waverly Press, 1960, pp. 348-353.

[2] The Book of Joshua.

[3] Painter, G.D., in The Vinland Map and the Tartar Relation, Yale University Press, 1965, p. 86.

[4] Flora, S.D., Hailstorms of the United States, University of Oklahoma, 1956, p. 9.

resulting directly from the impact of a large stone. "At Fort Archambault in Chad (Central Africa) in October 1958, a man was killed by a hailstone weighing over 50 grammes (diameter perhaps 6 cm.)."[5]

These devastating consequences justify the interest of various research projects throughout the world in gathering more information about hail, with the ultimate aim of modifying its influence. Alberta Hail Studies is one example of these.

The literature on world hail climatology is fairly abundant. A brief review of the world distribution of observed hail will be attempted, followed by a discussion of studies which provide opportunities for comparison of data with those of Central Alberta.

The Tropics

Hail is relatively scarce in the tropics. Figure 2 gives schematised isolines for the number of hail days per year in tropical Africa, India and Northeast Australia. Of these regions it appears that only the upland sections of tropical Africa have a point frequency of hail incidence greater than one day per annum.[6] Hailfall has been reported in Indonesia and other parts of Southeast Asia, but records are generally so sparse that no attempt could be made to draw isolines in this area of the map.

Tropical America, including the Caribbean, is also documented by Frisby

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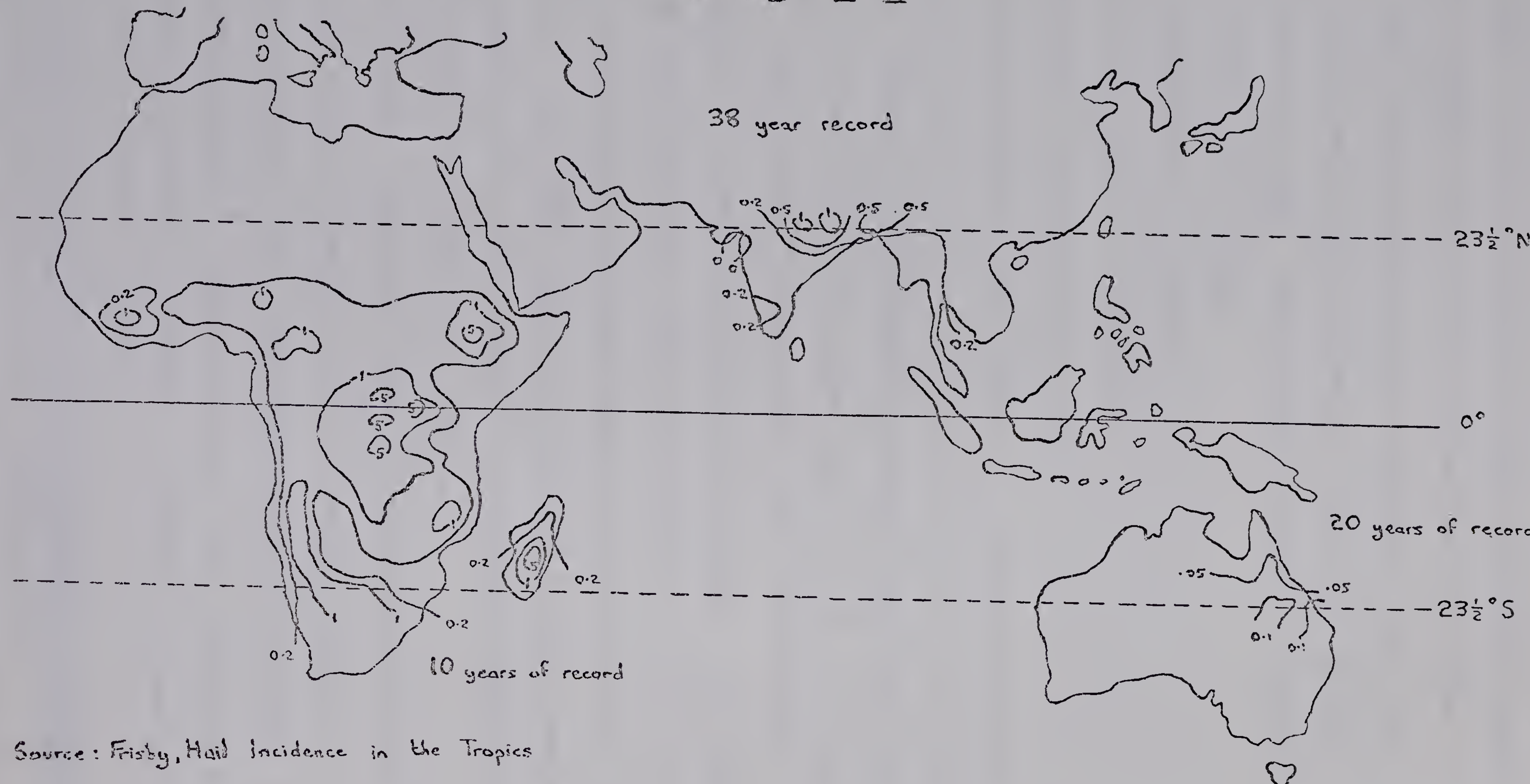
[5] Sansom, H.W., "The Occurrence and Distribution of Hail in Africa", Met. Mag., Vol. 95, No. 1128, July 1966, pp. 212-218.

[6] "In western Kenya hail is even more frequent than was originally suspected....The hail frequency at a point exceeds five storms per annum over much of the area, and reaches ten in parts of Kericho district. A more detailed temporary hail-reporting scheme introduced during August and September of 1965 indicated that hail was reported on 51 out of 61 days during these two months."
See loc. cit.

FIGURE 2



Source: Frisby, Hail Incidence in the Tropics

MEAN ANNUAL HAIL FREQUENCY FOR TROPICAL AFRICA, INDIA & N.E. AUSTRALIA.

and Sansom.[7] With the exception of Mexico, the point frequency of hail reported by most stations in the tropical Americas is of the order of 1-2 days per annum. Hail reports from the Caribbean are less common still, but in Mexico a great many stations have a point frequency of hail around ten days a year, and some even exceed this value. These figures are based on long-period means and are thus probably quite reliable.

Perhaps the most significant single reason for the generally lower frequency of hailstorms in the tropics is that the freezing-level is at a higher altitude than in mid-latitudes. Hence the convection process needs to be sufficiently intense to build clouds up to these greater heights. The jet-stream wind tends to blow at a higher level also; thus the horizontal wind-shear so important to the travelling storms of the Great Plains of North America can be achieved in the tropics only by storms of tremendous vertical extent. Swath-type hail activity does occur, but the swaths are usually short; hail tends to be somewhat sporadic in low latitudes. The comparatively high hail day values reported in Mexico lend weight to the idea that orographic uplift is a particularly important factor in the production of tropical hail. Mexico is, in the main, a plateau country with average elevation some 5,000 feet above sea level. Hail reports from Caribbean islands too are commonly from the mountainous lands above 3,000 feet.

Hail seems to fall at all times of the year in the tropics, but in any given area there is a definite season of maximum frequency. Frisby points out that a record of Costa Rican storms indicates two maxima, in April-May and August-September.[8] Mexican stations, on the other hand, appear unanimous in recording one maximum, in summer. In Cameroun the peak period is from

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[7] Frisby, E.M., and Sansom, H.W., Hail Incidence in the Tropics, unpublished report for Atmospheric Sciences Laboratory, United States Army Electronics Command, Fort Monmouth, N.J., September 1966.

[8] Frisby, E.M., The Hailstorms of Low Latitudes, paper prepared for the U.S. Army Research Organisation Conference on Tropical Meteorology, Miami, Florida, May 6-7, 1965.

February to April.[9]

Middle Latitudes

Mid-latitude hail has received a proportionately greater volume of copy, for hail occurs relatively more often. But point frequencies vary widely. A great deal of the research work on hail has been performed in the more afflicted areas of the middle latitudes; the focus has not been solely on its climatology, but also on its mechanics and possible suppression. These areas will be discussed briefly and put in perspective with regard to the general picture of mid-latitude hailfall.

In North America, hail research has been given considerable attention. The probable reason is that hail is most prevalent in the Great Plains of the interior, the foremost agricultural area of the continent; and the period of maximum activity in the summer tends to coincide with local growing seasons. Damage to crops is therefore high.

Figure 3 shows the distribution of hail days in the United States. It will be readily seen that most parts of the U.S.A. experience hailfall on only 1-3 days a year, and that the Great Plains region is the one extensive tract where this value is exceeded. Southeastern Wyoming is the area of maximum incidence, with 8-10 hail days per year, supporting the view of Lemons:

> "Hailstorms occur most frequently in the continental interiors at middle latitudes, diminishing seaward, and becoming less frequent also as they approach the equator and the poles."[10]

The onset of the hail season progresses northwards, so that in Alberta it occurs in mid-May, compared with late March in Illinois and early or mid-April in Colorado. The southern prairies of Canada receive considerable summer hail.

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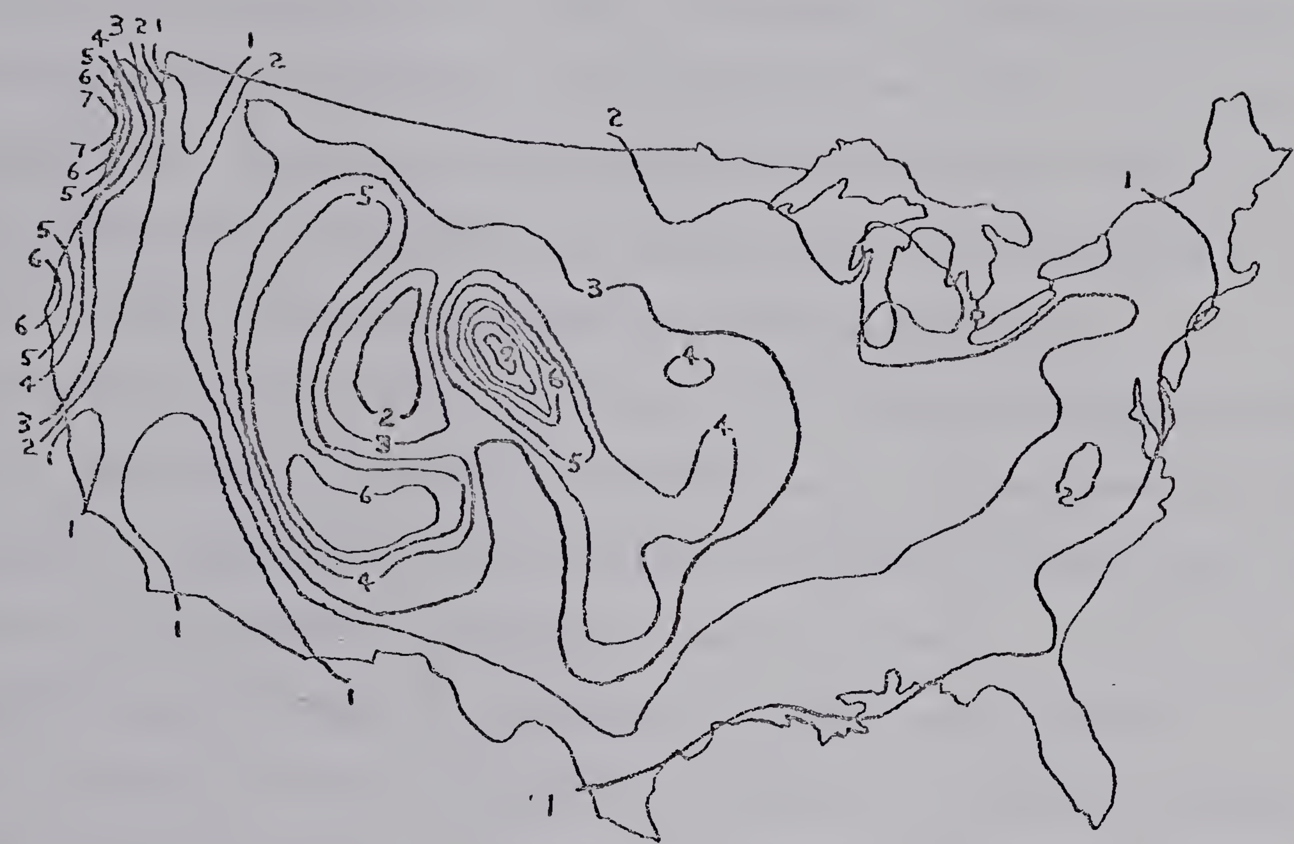
9 Frisby and Sansom, op. cit., p. 36.

10 Lemons, H., "Hail in High and Low Latitudes", Bull. Amer. Met. Soc., Vol. 23, No. 2, February 1942, pp. 61-75.

FIGURE 3



Based on 219 first-order stations

Source: Flora, S.D., Hailstorms of the United States, p. 24.

AVERAGE ANNUAL NUMBER OF DAYS WITH HAIL IN THE U.S.A., 1904 - 1943.

In southern Ontario, tobacco is particularly susceptible to its ravages - in the period 1934-37 the average loss to risk ratio[11] in insuring this crop was 94 per cent.[12]

Although North American hail damage is greatest in the Plains region, it is certainly not confined to it. Fruit, for example, is seriously affected by the bruising impact of hailstones, and all the states of the union report some damage each year. But the only area outside the Great Plains where any detailed information on local hail climatology seems to be available is in New England. A small network of volunteer observers is maintained.

The lee of the Rocky Mountains appears to be the major hailstorm "breeding ground" of the continent, and it is here that most of the research has been concentrated. Perhaps the first hail-reporting network in North America was that set up in the immediate vicinity of Denver, Colorado. It has since been followed by similar schemes in northeastern Colorado and in Alberta. A further considerable amount of work has been done in the American mid-west on crop-hail insurance figures. Analysis of information furnished by these various hail-reporting networks has yielded some data from each area which may be compared with similar material compiled by Alberta Hail Studies.

The common occurrence of hail to the east of the continental divide in North America is paralleled elsewhere.

> "In several other areas throughout the world hail appears to be more frequent in the locations to the lee of a mountain range than to the windward side of the same range. For example, the hail region in New Zealand is in the lee of the Southern Alps. The prevailing winds are westerly and the hail frequency is higher on the eastern side of the mountains, in Canterbury in particular, than on the western. The country near Timaru and Temuka is not unlike some parts of Colorado and Wyoming. The hail incidence is high in both locations. During the dry northeastern monsoons in

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[11] Defined simply as the loss estimated by insurance adjusters divided by the risk insured.

[12] Flora, op. cit., p. 180.

> India hail is most frequent and often severe. The hail occurs on the southern or southwestern (or lee) flanks of the Himalayas and also in the southern portion of Hyderabad, which is at a lower elevation than the northern sections of the state."[13]

This state of affairs also seems to apply to the hail areas of southern Switzerland and North Italy, which have been the scene of seeding experiments and lie to the east and south of the main range of the Alps. In fact some parts of Europe have more frequent hail than anywhere in the United States. Paris, France, has an annual frequency of ten days, and Württemberg averages thirteen (possibly due to the inclusion of graupel and small hail in the observations; this is the reason for the rather high hail day values shown in Figure 3 for the Pacific Northwest of the U.S.A.).[14] Southern Europe gets most hail in winter, while the storms of mid-latitude Europe are commonest in spring and late summer.

Damaging hailstorms are not at all rare in Europe. In the Mediterranean regions they have been mentioned in the writings of early civilisations. Average annual point frequencies seem to vary quite widely; for example, two hail days per annum are experienced at Athens, seven at Beirut, and nine on the island of Malta.[15] For Morocco, Sansom gives values of 1-2 on the coastal plains and up to five in the Atlas Mountains.[16] The severity of some Mediterranean hailstorms is exemplified by that of June 13, 1930, when twenty-two persons were reported killed in the Siatista district of Macedonia. Only five weeks later, on July 16, seven more met their deaths through hail in southern Bulgaria.[17]

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[13] Powell, G.L., <u>The Relationship of Physiography to Hail in Alberta,</u> unpublished M. Sc. thesis, University of Alberta, Edmonton, 1961, pp.10-11.

[14] Flora, *op. cit.*, p. 184.

[15] *Ibid.*, p. 185.

[16] Sansom, *op. cit.*, p. 215.

[17] Flora, *op. cit.*, p. 185.

There have been some excellent accounts of damaging storms in mid-latitude Europe; severe hailstorms are encountered even in the extreme west, though rather less frequently. Feteris has analysed a storm of June 19, 1954, which caused havoc in a small area of The Netherlands,[18] and there are some well-documented examples of swath-type hail activity in England.[19] The writer has also found references to extensive property damage by hail in Leipzig, Germany (in the year 1860), and Budapest, Hungary.[20] Prohaska demarcated certain preferred hailstorm tracks in Austria around the turn of the century,[21] and it seems that hail has been a subject of interest and concern in Central Europe for a very long time. The Swiss Hail Insurance Company, for instance, was founded in 1880.

In the U.S.S.R., according to Pastukh and Sokhrina, most areas experience less than two hail days per year.[22] Battan, however, states that:

> "There are two regions where this is not the case. Along a roughly northeast to southwest strip between about Alma-Ata and Samarkand, hail frequency reaches 5-6 days per year.
>
> The highest frequency of hail occurs in the region of the Caucasus. Just north of the Caucasus Mountains there is an average of 4-5 hail days per year. South of the mountains in the state of Georgia the frequency is as high as eight hail days per year. The number of days with hail is about four per year in nearby Armenia and Azerbaijan."[23]

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[18] Feteris, P.J., "£330,000 Hail Damage in Fifteen Minutes; Analysis of a Devastating Hailstorm", Weather, Vol. 10, No. 7, July 1955, pp. 223-232.

[19] For instance, see Browning, K.A., and Ludlam, F. H., "Airflow in Convective Storms", Quart.J. Roy. Met. Soc., Vol.88, No. 376, April 1962, pp. 117-135.

[20] Flora, op. cit., p. 185.

[21] Weickmann, H., "Observational Data on the Formation of Precipitation in Cumulo-Nimbus Clouds", in Thunderstorm Electricity, Byers, H.R. (ed.), University of Chicago Press, 1963, pp. 104-105.

[22] Pastukh, V.P., and Sokhrina, R.F., "Hail in the U.S.S.R.", Trudy Glavnoi Geofiz. Obs., No. 74, 1957, pp. 3-24.

[23] Battan, L.J., Recent Studies on Hail and Hail Modification in the Soviet Union, Scientific Report No. 21, Institute of Atmospheric Physics, University of Arizona, October 5, 1965.

It appears from Battan's paper that the majority of Soviet hail research is concentrated in the Caucasus, and upon forecasting, radar observations of storms, and suppression experiments.

Information regarding hail in Central and Eastern Asia is lacking, though it is certain that some areas are hail-prone. The western provinces of China are known to suffer severe storms, and similar reports have come out of Mongolia and the interior plateaux. But no worthwhile climatological data on hail are available for much of Asia outside the tropics.

In the Southern Hemisphere the extra-tropical continental area is small, and hail observations are limited. But there are several regions where hail incidence is relatively high. The Canterbury Plains of New Zealand have already been mentioned; the extreme southeastern part of Australia is a similar area. South of the equator, only the republic of South Africa has a major hail research programme, however. More than five hail days per annum at a point are reported over a wide area; the observing network is located in the Transvaal and operated throughout the year by the National Physical Research Laboratory of the Council for Scientific and Industrial Research. In South America, only the hail belt of Paraguay and Northwest Argentina is outside the tropics. Most stations in Paraguay record 2-3 hail days a year, and there is a maximum in October-November,[24] while the Argentinian foothills country of the Andes experiences most hail activity in the summer months.

Research Projects Investigating Hail Climatology

(i) The Denver Network

One factor in the establishment of this network in 1949 was the interest of United Airlines, whose aircraft had many times sustained

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[24] Frisby and Sansom, op. cit., p. 33.

damage aloft from hailstones in this area.[25] The observing stations, varying in number from twelve in 1949 to around fifty in each year since 1951, cover about 150 square miles. They soon verified that network hail reporting provided a more realistic picture of frequencies of occurrence than did the official meteorological stations. The Denver network might almost be regarded as a pilot scheme, but some data on hail days, stone size distributions and times of onset are available for the years 1949-1958.[26]

(ii) The Colorado State University Network

Centered on New Raymer in north-eastern Colorado, where the weather radar is situated, the system includes both volunteer observers and hail-impact recorders. The project area covers some 6,500 square miles, and climatological data for the years 1960 and 1961 are available in a paper by Schleusener and Grant.[27] They include information on hail days, storm track directions (better documented in the radar climatology reports), times of hail onset, duration of storms and intensity of fall, the indicator used here being the degree of ground coverage.

(iii) The New England Network

Donaldson has given an account of radar investigation of some New England hailstorms, with which he includes details of 317 hail reports of the 1956, 1957 and 1958 hail seasons. He gives no indication of the area covered (the radar site was at Blue Hill, Milton, Mass.), but

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[25] For hail damage to aircraft, see Crossley, A.F., "Hail in Relation to the Risk of Encounters in Flight", Met. Mag., Vol. 90, No. 1065, April 1961, pp. 101-110.

[26] Beckwith, op. cit.

[27] Schleusener, R.A., and Grant, L.O., Characteristics of Hailstorms in the Colorado State University Network, 1960-61, Atmospheric Science Technical Paper No. 20, Civil Engineering Section, Colorado State University, Fort Collins, Colorado, October 1961.

analyses are performed on maximum size of observed hail and duration of fall.[28]

(iv) Alberta Hail Studies

An appraisal of the data compiled by this project follows in Chapter II.

(v) The Illinois State Water Survey

There has been considerable research into Illinois hail day statistics as revealed by U.S. Weather Bureau stations and sub-stations, and into the incidence of damaging storms shown by the records of the Crop-Hail Insurance Actuarial Association of Chicago. A network of roughly a thousand volunteer observers within 100 miles of the Survey radar site was set up in central Illinois in 1958, essentially for the purpose of evaluating attempts at radar detection of hail, and hence possible forecasting.[29] But their reports do include stone sizes and times of onset.[30]

(vi) National Physical Research Laboratory, South Africa

The hail-reporting network, which covers an area of about 1,000 square miles and includes Johannesburg and Pretoria, has been in operation since October 1962. Around a thousand volunteers observe hailfall. The peak season is summer, and data on maximum hail size accompany hail day statistics for three summers in a

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[28] Donaldson, R.J., Chmela, A.C. and Shackford, C.R., "Some Behaviour Patterns of New England Hailstorms", in Physics of Precipitation, op. cit., pp. 354-368.

[29] Stout, G.E., Blackmer, R.H., Jr., and Wilk, K.E., "Hail Studies in Illinois Relating to Cloud Physics", in Physics of Precipitation, ibid, pp. 369-381.

[30] Stout, G.E., et al., The Hail Hazard in Illinois, preliminary report for the Crop-Hail Insurance Actuarial Association, Chicago, 1959.

paper by Carte.[31] Individual storms of particular interest have also been documented in detail.[32] Further material of a climatological nature is to be found in two more recent papers.[33,34]

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[31] Carte, A.E., "Hailstorms in South Africa", South African Weather Bureau Newsletter, No. 193, April 1965, pp. 58-61.

[32] Idem, Hailstorms in Johannesburg, Pretoria and Surroundings on January 15 and 16, 1964, CSIR Research Report 228, Pretoria, South Africa, 1964, pp. 1-26.

[33] Idem, "Features of Transvaal Hailstorms", Quart. J. Roy. Met. Soc., Vol. 92, No. 392, April 1966, pp. 290-297.

[34] Carte, A.E., and Kidder, R.E., "Transvaal Hailstones", Quart. J. Roy. Met. Soc., Vol. 92, No. 393, July 1966, pp. 382-391.

CHAPTER II

ALBERTA HAIL STUDIES DATA

The farmer network has been active since 1957, so that data from it are available for the ten years 1957 to 1966 inclusive. The present study is limited to information derived from the hail cards; the reporting area is shown in Figure 1. Post Office mailing lists are used to ensure that a supply of cards for each hail season reaches all farmers inside the boundaries and a number of individuals living in the towns as well; the cards are sent out in early May, with provision for the replenishment of the supply during the summer if this becomes necessary. All in all, the number of potential observers is around 26,000, or more than one to a square mile.

The shortcomings of the data may be subdivided, on the basis of their source, into:

(i) Network failings,

(ii) Problems with individual reports.

(i) The Network

It must be borne in mind that there are essentially two different types of reports received by Alberta Hail Studies: those volunteered by the farmer, either in the mail or over the telephone, and those solicited from him by the project (generally in surveys of particularly interesting storms), either by car sortie into an area or on the telephone. If the numbers of unsolicited reports from different years are to be compared (as a reflection of hail activity within the project area, for instance),[1] it has to be assumed (a) that the network, and the location of the reporters in it, do not change from year to year, and (b) that the response, i.e. the proportion of people receiving cards that actually sends in reports, does not change

[1] The number of survey reports collected depends entirely on a decision by the Hail Studies to run a survey.

either.

In 1957 the project area was somewhat smaller than it is today. The boundaries in use at the present time were adopted in the spring of 1958. Provided that the change between 1957 and 1958 is kept in mind, therefore, assumption (a) is fairly reasonable; fluctuations in the number of actual reporters in the network have not been serious. In 1961 requests for reports were sent to some 21,000 householders; so it would appear that not all farmers in the project area received them. By 1963 the mailing list had been increased to a maximum of over 26,000; rural depopulation has caused a decrease from 1964 onwards. The change in the total of potential observers is not sizeable, and variation in the numbers of those who actually report to Alberta Hail Studies will be less significant still.

The question of the response accorded to the project (an estimate of which would be useful in assessing the validity of assumption (b)) has been treated theoretically by Carte.[2] He concluded that in 1961 about 29 per cent of the potential observers reported. Whether this figure has increased since 1961 is difficult to ascertain, since the method he employed is no longer applicable. With the extension of the survey technique, expansion of the interests of Alberta Hail Studies, and good publicity in recent years, an increase seems possible. But this may well be offset by farmers who have decided that as hail suppression is still not a scientific proposition the project has failed, and is not worthy of their support! The problem is that there is no really objective way of assessing the response to any given storm with complete certainty.

At first sight it would appear that this could be done for a surveyed storm where all farmers in the hailswath were contacted, simply by expressing the number of unsolicited reports as a percentage of the total. But in actual

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[2] Carte, A.E., Some Characteristics of Alberta Hailstorms, Stormy Weather Research Group, Scientific Report MW-36, McGill University, Montreal, August 1963, pp. 1-15.

practice it is found that an intensive survey has the effect of obtaining reports from people who would otherwise have mailed in their observation. In other words, it cuts down the number of cards which would have been sent in had the storm not been surveyed. This matter is referred to again in Chapter IV, when the definition of a "major hail day" is discussed.

Another response problem is that many amateur observers will only report hailfall which they themselves consider to be significant, for example, one which damages their crop. Although it is emphasised that every hailfall, even the smallest, should be reported, it is known that this instruction is frequently disregarded. And even the most reliable of observers, who would normally inform on all hail encountered on their property, may be absent temporarily for a variety of reasons.

Areal variation in the network density is another factor to be borne in mind. It may be desirable to compare the number of unsolicited reports for a given day in one part of the project area with those in some other. But the two sectors may have a markedly different density of population, and a form of "weighting" must be undertaken if meaningful conclusions are to be drawn.

In summarising this section, it has to be pointed out that all information derived from hail cards is simply what the network has revealed concerning hail in the area, and nothing more. The assumption has then to be made that a representative picture of Central Alberta hail activity is given therein.

(ii) Individual Reports

Over the years the questions on the cards have changed in an evolutionary process of improvement. This has led to the drawback that certain of the data are only available for a part of the ten years, some for a very short time indeed. In the discussions of data which form the body of

this thesis, the number of years in which information is available to each particular analysis will be stated.

Reports mailed or telephoned in by the farmer are usually the most complete and accurate. The details are generally written down quite soon after the hailfall while still fresh in the person's mind; for this reason these observations are the most reliable in providing accurate information. On the other hand, survey reports are sometimes obtained two or three days after a storm. By this time the farmer's recollection of it is hazy, especially regarding the time of the hail, but also in many cases concerning some or all the characteristics of the storm. This is particularly true if there has been another hailfall on the property in the meantime.

Answers to the questions on the card vary a great deal in their usefulness. The date of the storm can be checked by other reports or against the weather radar log-book, if it seems necessary. Location of the hail occurrence is defined in terms of the quarter-section, township and range land-location system employed in Alberta, and can thus be pinned down within half a mile. It can be checked to some extent in the Green Card Index, on the map, or against the radar log; if there is still a query, the observers may be contacted, but this step is rarely necessary.[3] However, before a report is accepted by Alberta Hail Studies, it has to be made fairly certain the the two prime factors, i.e. the date and location of hailfall, are correct.

Most of the remaining information on each card has virtually to be taken on trust from the farmer. Onset time of hail is most reliable in the case of unsolicited reports. It can be checked roughly, in the same fashion as the date of the occurrence; for example, an a.m. time which should be p.m. can usually be spotted. An oft-noted characteristic of the reported time of

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[3] The Green Card Index is a file containing the name, land-location, postal address and telephone number of anyone who has ever furnished a report to Alberta Hail Studies.

commencement of hail is the bias of observers towards the quarter, half or whole hours; this failing also pervades the hailfall duration reports, where the bias favours multiples of five minutes.[4]

Other simple checks which can be performed include:

(a) ensuring that the "Most Common Size" of stone reported is not larger than the "Largest Size"; if so, the procedure followed is simply to reverse them,

(b) seeing whether a negative reply to the "was there any soft hail?" question is followed by a specified size for the soft hail: in this case it is assumed that the reply should have been in the affirmative,

(c) checking that the land-location of "another property on which the farmer knows it hailed" is not the same as that which his own hail report is concerned with.

When a hail card arrives in the Hail Studies office, it is first of all recorded in the Hail Card Log (see Figure 4). The report is then plotted on a small-scale map of the project area, using a numerical code to indicate the maximum size of the stone received;[5] this shows all the observations from the storms of one particular day and enables the reported geographical distribution of hail activity to be grasped at a glance. Then the card is checked through the Green Card Index, and finally the information on it is coded for punching

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[4] Douglas, R.H., The Study of an Alberta Hailstorm, Stormy Weather Research Group. Scientific Report MW-35, McGill University, Montreal, December 1961, p. 1.

[5] The numerical code is as follows:

0 Unknown
1 Shot
2 Pea
3 Grape
4 Walnut
5 Golfball
6 Larger Than Golfball

FIGURE 4 - PAGE OF THE HAIL CARD LOG

STORM(S) OF ....July 4........ 1966

DATE OF RECEIPT	NUMBER OF REPORTS: FROM FARMER (F) MAIL	TEL.	BY SURVEY (S) CAR	TELEPHONE	CUMULATIVE TOTAL F	F + S
July 4				1(7)		1(7)
JULY 5	0,1,0				1	2(7)
July 6	3,0,0				4	5(7)
July 7	0,1,0				5	6(7)
July 11	1,0,0				6	7(7)
JULY 31	6			1 (8)	6	7 (8)

LARGEST HAIL	NO. OF REPORTS		TOTAL
0 UNKNOWN	I	1	
1 SHOT	III	4	
2 PEA	III	3	
3 GRAPE			
4 WALNUT			
5 GOLFBALL			
6 LARGER			

on the IBM card, so that Automatic Data Processing methods can be used in further analysis. There is one punched card for each individual hail report.

Both the methods outlined above - computer programming to scan individual cards, and use of the Hail Card Logs and summaries - have been employed here. For each analysis described in the following chapters the data will be discussed and the method of investigation specified. There is not room to go into all the procedural details in this chapter. The computer work, however, is discussed in the following chapter, since it is relatively lengthy and is sufficiently important to the remainder of this thesis to merit separate treatment.

CHAPTER III

THE COMPUTER PROCESSING

In the previous chapter, the characteristics of Alberta Hail Studies data were dealt with. Transferring these data from the hail report cards to punched cards has raised some problems. One or two improvements could be made in the coding scheme, but basically the trouble lies in the comparative inflexibility of computer analysis, and the subjective interpretation of some answers on the cards which is necessary in consequence. This matter of interpreting indefinite data to make them rigid and acceptable to the computer is an important one.[1]

A problem associated with introducing refinements to the coding technique is that the reports from previous hail seasons have already been punched up without them. Therefore any programme developed to utilise the further information contained in the new punched cards would be inapplicable to the earlier data. Short of undertaking the mammoth task of re-coding and punching these earlier reports, there is nothing that can be done about this.

For all its limitations, computer analysis has the advantages of being fast, efficient and reliable. It is in fact the only practical way of scanning more than thirty thousand cards for some of the investigations conducted in this study. However, there is obviously no point in using the computer for jobs not involving a search of individual cards. Examples are examination of network hail day values (easily obtainable from the various Hail Card Logs) and stone size distributions, which have been compiled from the logs each year.

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[1] Appendix A shows the coding scheme used in transferring data from the hail report cards to IBM punched cards.

An understanding of the different methods used in the computer processing is necessary before the reader can fully appreciate the advantages, disadvantages, implications and conclusions of the work described in later chapters. It is most convenient to deal with it under one heading rather than in piecemeal fashion as the thesis unfolds.

Essentially the aim of the computer programming is fourfold. It is to examine the temporal (on both a year-to-year and a seasonal basis) and spatial variation of the properties of individual hailfalls. Two approaches to the spatial variation question are used: first, a simple investigation of the areal aspects of the variation, and second, a grouping of data into classes of "distance from the Rocky Mountains", to test the hypothesis that this factor does affect some of the properties or parameters of particular hailfalls. As previously noted, the pattern of frequent hail occurrence in the lee of a major mountain range recurs in many localities throughout the world.

The inflexibility of computer analysis has already been referred to. Whereas the data derived from summaries and logs (for example, those used in Chapter IV) are not strictly defined in terms of area, it was thought desirable to have a rigidly delineated area for the purposes of spatial analysis. All conclusions drawn from the spatial segments of the investigation could then definitely be stated as characteristic of hailfall in this well-defined area. Only reports from within the area shown in Figure 5, henceforth referred to as "Analysis Area", were subjected to regional analysis on the computer. For convenience in programming, the lines bounding the Analysis Area always coincide with either the project area outlined in Figure 1 or the area in which farmers received report cards - the boundaries of this region are those of Post Office districts.

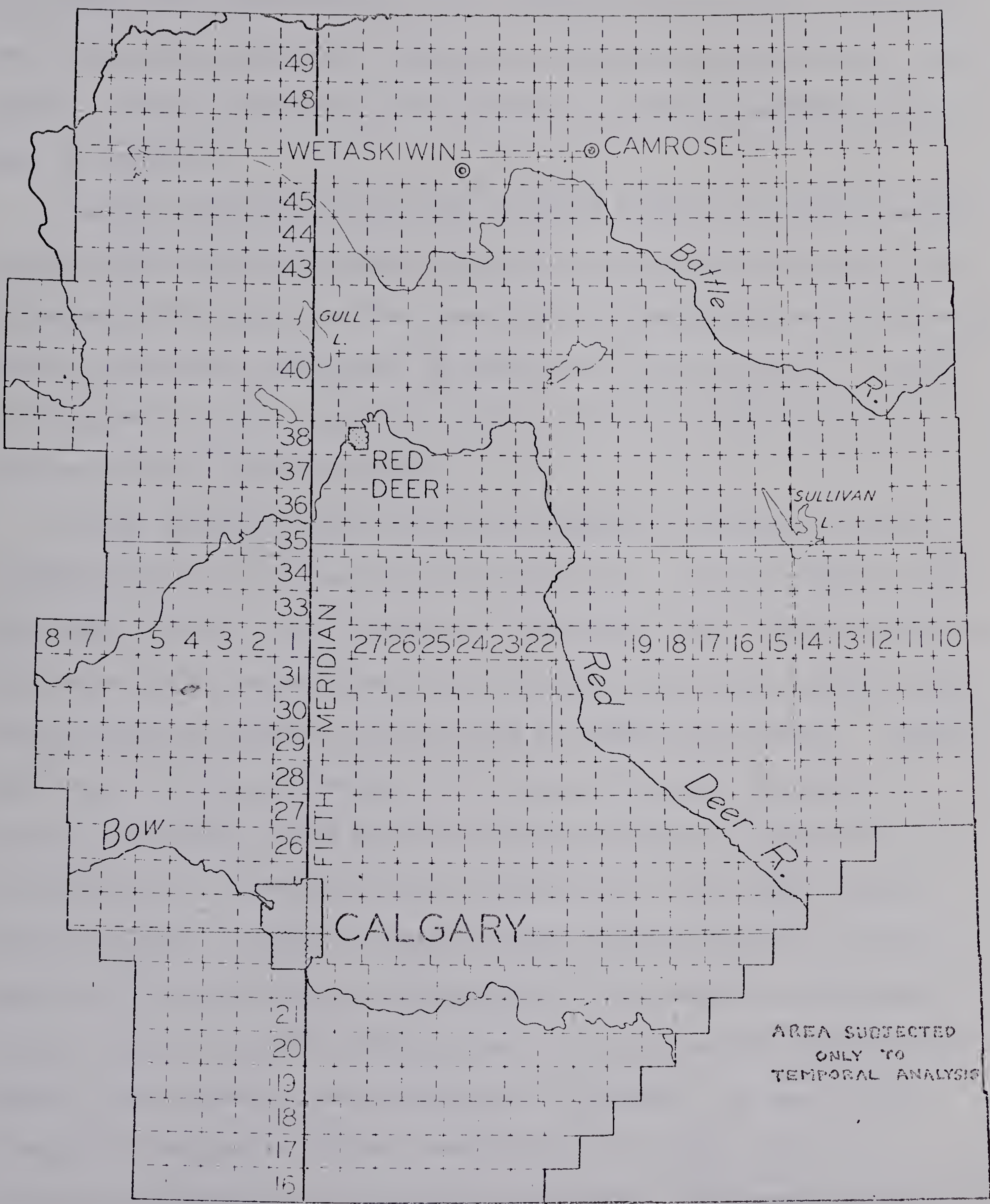

FIGURE 5 - THE ANALYSIS AREA

The Four Major Analyses

Grouping of all cards from Townships 16-50 and Ranges 10-30 West of the Fourth Meridian and 1-9 West of the Fifth into individual years presented no problems. Year-to-year variations were examined in this manner, and April and October were included. No cases of inadequate samples were encountered.[2]

Seasonal variations in this same area were treated by grouping together all the cards from the ten months of May, the ten months of June, and so on, during which the project has been operating. The analysis therefore indicates seasonal differences summed over the whole of the ten year period. During April and October, only one or two reports have been collected; they have thus been omitted from the analysis.

For the straightforward regional investigation the Analysis Area was divided into 216 small areal units (see Figure 6). As far as possible these were equal in area, at four townships or 144 square miles. Since the project area covers 30,000 square miles, and over 30,000 reports are available, each division might be expected to have around 150 reports for analysis. However, because of the irregualar shape of the Analysis Area, and the need to identify that portion which has been regularly subject to cloud-seeding, it is not possible to have all the units equal in area. This fact, together with the varying population density and hail frequency in Central Alberta, means that to ensure that the minimum sample of 100 reports is maintained in each region, a further combination into 122 units and the elimination of Ranges 10 and 11 west of the 4th Meridian is necessary. In most of the straightforward spatial analyses undertaken in this study, maps of the variation of different hail parameters are plotted. The average values of

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[2] An arbitrary figure of 100 reports is considered to be an adequate sample for the purposes of this thesis.

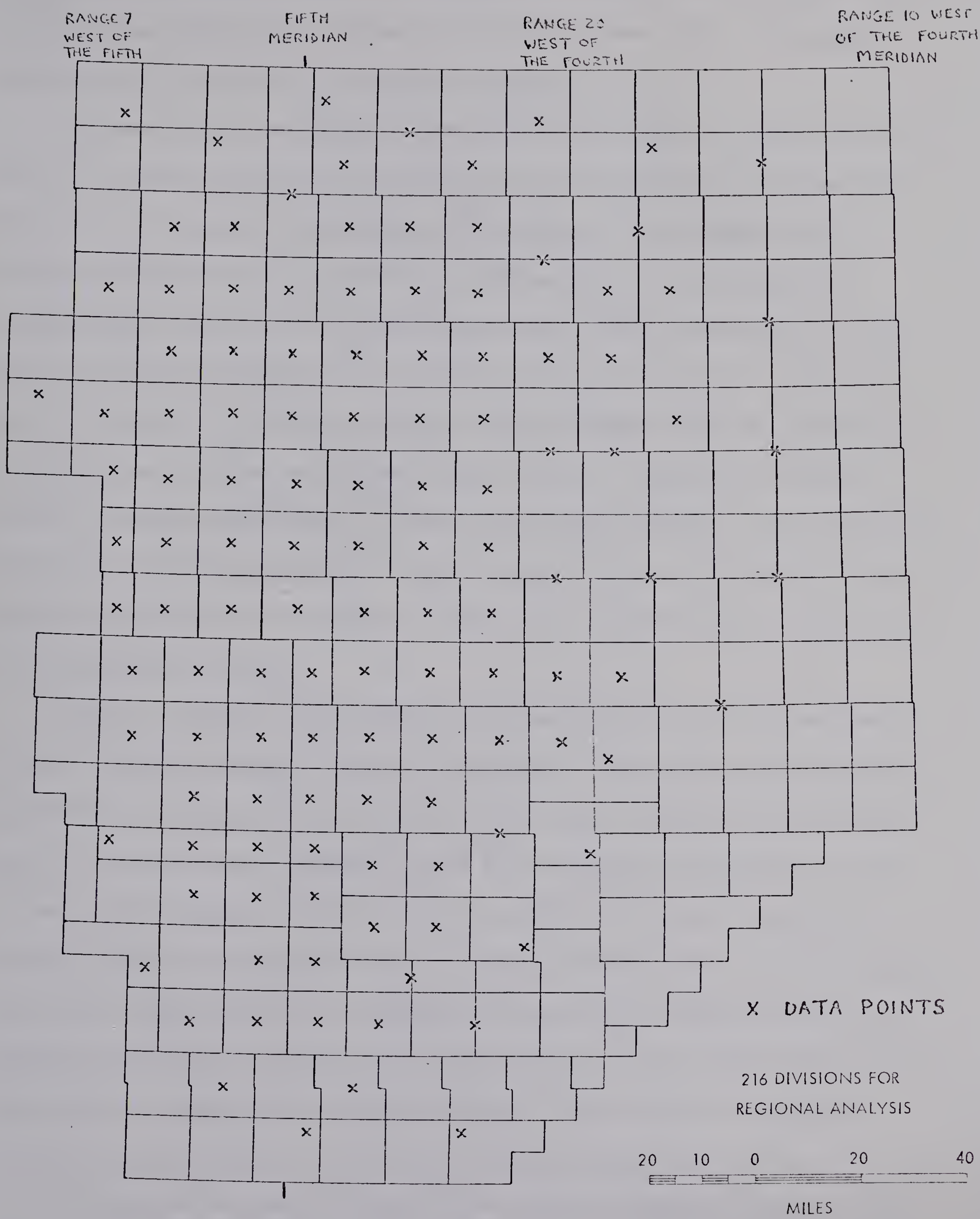


FIGURE 6 - REGIONAL COMPUTER ANALYSIS

these parameters are plotted at the geometric centres of the 122 areal units to which they refer, and isolines interpolated between them. The positions of these 122 "data points" are shown in Figure 6.

The problems of any regional analysis are well known. Ideally several sets of boundaries should be adopted, and the investigations performed with each of them in order to ascertain if the choice of them significantly affects the final results. There is a difficulty too in the fact that unequal areas lead to varying sample populations being available for study; this is accentuated here by the varying frequency of reports in each areal unit. Probably in no case do two units have the same number of reports for treatment, so that the conclusions reached could be regarded as having exactly the same significance. Despite all these drawbacks, this is probably the first time that the hailfall patterns shown by so many reports over so large an area have been studied in such detail, and the analysis is therefore of considerable interest.

Figure 7 indicates the township groupings employed in the investigation of the effects of distance from the mountains.[3] The computer was programmed to divide the Analysis Area into forty-seven strips running in a northnorthwest to southsoutheast direction. Each is one Range or six miles from west to east, and "zigzags" from southeast to northwest in order to preserve a roughly constant distance from the main range of the Rockies. On the diagram, the class numbers used in programming the computer run along the western and northern sides of the Analysis Area, while figures on the eastern and southern sides refer to approximate average distances from the main range of the

[3] As far as the writer is aware, the only other specific study of this factor is related to the Argentinian Andes, and investigated only hail days, crop damage and upper winds. See Grandoso, H.N., "On the Distribution of Hailstorms at the Lee of the Argentinian Andes", Abstracts of the Third Severe Local Storms Conference, November 12-14, 1963, Urbana, Illinois, Bull. Amer. Met. Soc., Vol. 44, No. 9, September 1963, p. 600.

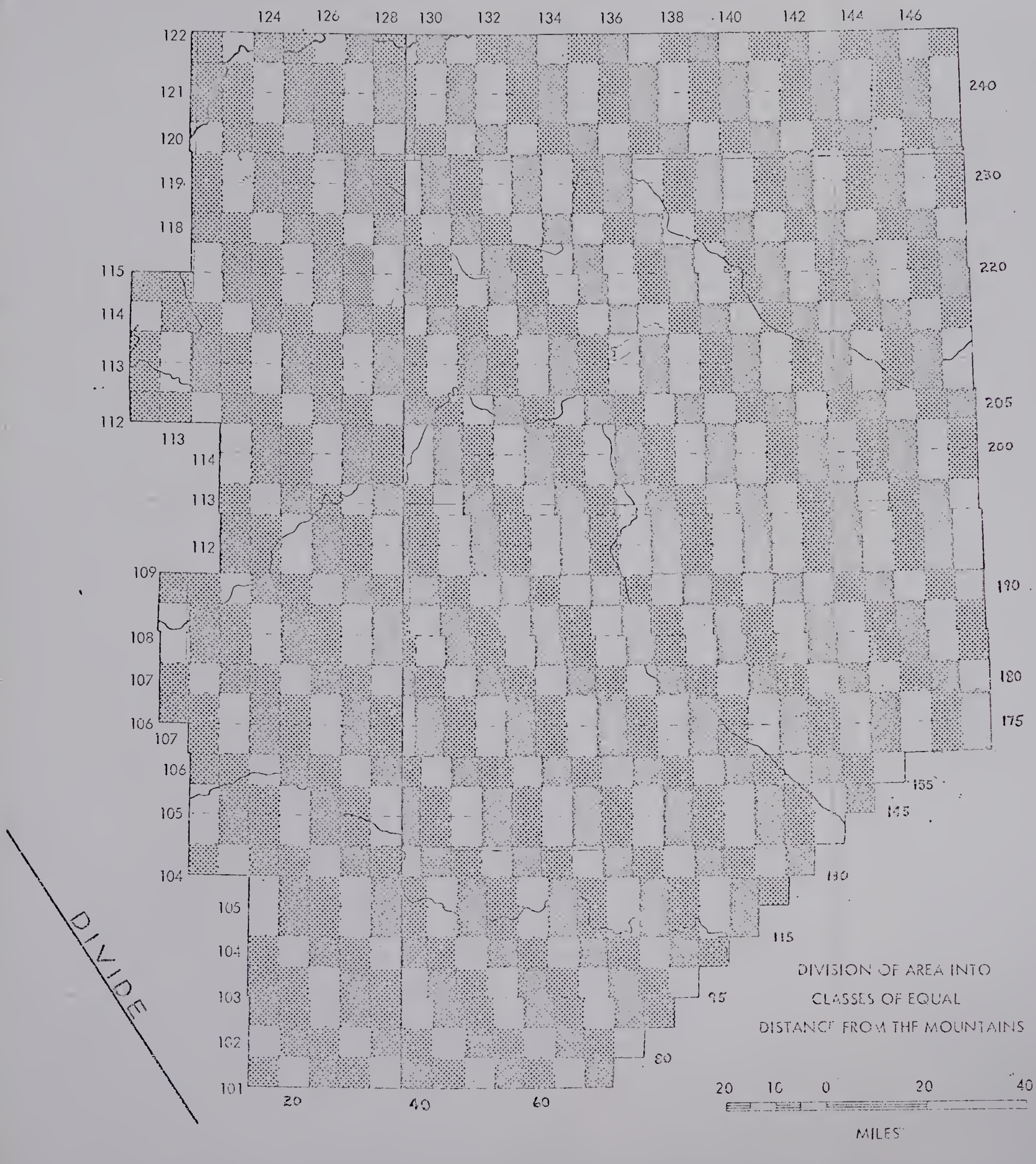


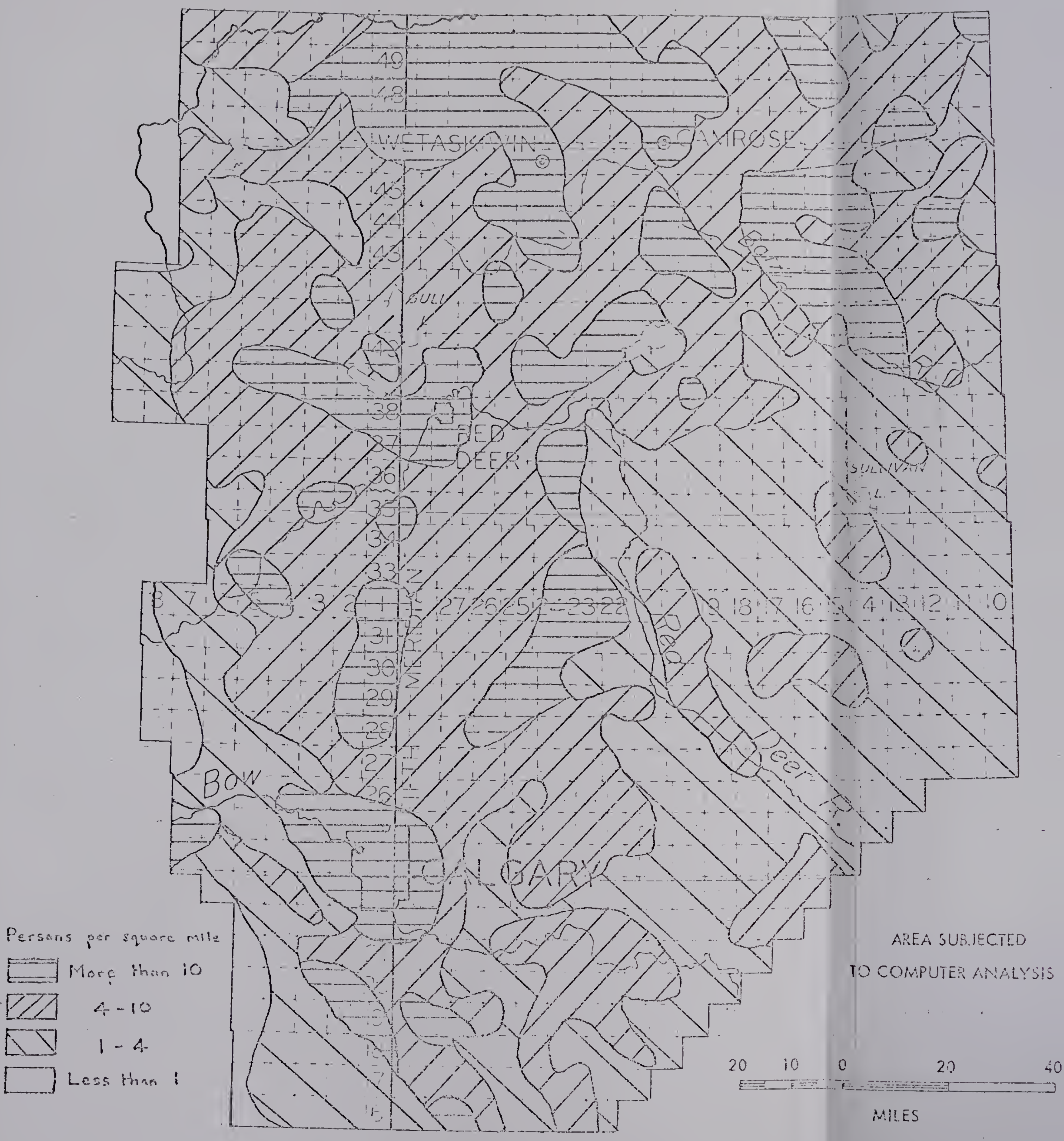
FIGURE 7 - "DISTANCE FROM MOUNTAINS" ANALYSIS

Rockies (represented by the thick straight line in Figure 7). The reports from each class are considered together; values of the different parameters can be evaluated for each class and their variation perpendicular to the mountains examined.

A problem with this analysis is that vastly different numbers of reports have been received from the various classes. The very nature of the division means that Class 122 covers a much greater area than those on the southwestern and northeastern fringes of the area, which have furnished so few reports that representative samples are not available. One hundred reports having been fixed as the threshold value, only Classes 106-138 can be used in the analysis. Classes 101-105 contain 106 reports altogether, and are regarded as a composite unit with a weighted mean distance of 33 miles from the mountains. Class 139 has only 88 reports, but since Classes 140-147 have enough reports (146) to justify consideration as another composite unit, with weighted mean distance from the mountains 218 miles, Class 139 has been allowed to stand by itself.

Another interesting point is that one might anticipate the number of reports per class to rise steadily from the southwest of the Analysis Area to a maximum around Class 122, which covers the largest area, and then decline to the northeast. In actual fact the maximum of 1,818 reports does occur in Class 122, 120 miles from the mountains. But no class to the northeast of Class 125, i.e. more than 135 miles distant from the divide, has as many as a thousand reports, while every one of Classes 111-125 has more than a thousand. The reason for this concentration of reports in the southwestern half of the region is probably to be found in the fluctuating density of population across the project area (Figure 8).

In various places totals of unsolicited reports, observations of large hail, grand totals of cards scanned in the analysis and so on are counted by



Source: Atlas of Canada, 1957

FIGURE 8 - ANALYSIS AREA POPULATION DENSITY

the computer. The procedure is straightforward. Any apparent discrepancies in these totals, and particularly the grand total of hail cards amassed over the ten -year period, stated at several points in this study, may be explained in two ways.

Firstly, only reports from Townships 16-50 and Ranges 10-30 West of the Fourth and 1-9 West of the Fifth Meridian were reviewed by the computer in the temporal investigations. This area is outlined on Figure 5, and its chosen boundaries resulted in seventy-two reports received by Alberta Hail Studies being entirely eliminated from all computer processing. Secondly, the rigid area employed in spatial analysis approximates closely to the project area. Thus it does not include the region to the southeast of Gleichen, Hussar and Dorothy which, although lying beyond the project boundaries, has furnished around two hundred of the reports used in the temporal analysis. Hence the total hail reports obtained by Alberta Hail Studies from 1957 to 1966 may be regarded as the 30,384 cards scanned in the temporal examinations, plus the 72 cards not analysed at all. This total is 30,456.

CHAPTER IV

NETWORK HAIL DAYS

Logs of returned report cards have been kept since 1957. Each day for which at least one substantiated report is received constitutes a "hail day". Table I shows the numbers of hail days per month since the inception of the project, and is based for the most part on examination of the hail card log books.[1]

TABLE I - NETWORK HAIL DAYS

Year	May	June	July	Aug.	Sept.	Total
1957	-*	23	26	20	11	80
1958	-*	21	19	16	4	60
1959	3	22	17	21	4	67
1960	-*	21	17	21	0	59
1961	5	14	12	3	3	37
1962	9	22	25	19	5	80
1963	9	23	25	18	5	80
1964	8	22	18	12	5	65
1965	12	15	22	15	7	71
1966	7	20	22	12	5	66
Totals	53*	203	203	157	49	665
Means	7.6*	20.3	20.3	15.7	4.9	68.8
General Hail Day Probability	24%	68%	66%	51%	16%	48%

Source: Alberta Hail Studies records

* In 1957, 1958 and 1960, report cards were not sent out before the end of May. Thus these years have been excluded from the compilation of the May values.

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[1] As the 1962 log is not of the standard layout, a simple computer programme was run on the 1962 punched card data to obtain the values for Table I.

It will be readily seen that June and July are the most active months. Either of them may have more hail days than the other in any given year, but June is the more consistent, varying from 14 in 1961 to 23 (1957 and 1963). The July range is from 12 hail days in 1961 to 26 in 1957. The likelihood of a hail day (hail days as a percentage of the total days in the month, for the whole of the ten-year period) is 68 per cent in June and 66 per cent in July. Comparable figures for the other months are 24 per cent for May (seven years only), 51 per cent for August and 16 per cent in September.[2]

TABLE II - NETWORK MAJOR HAIL DAYS

Year	May	June	July	Aug.	Sept.	Total
1957	-*	5	9	4	1	19
1958	-*	2	1	2	1	6
1959	0	8	4	3	0	15
1960	-*	5	7	2	0	14
1961	0	4	0	0	0	4
1962	0	8	7	2	0	17
1963	0	5	7	5	0	17
1964	0	5	5	1	0	11
1965	2	4	9	2	0	17
1966	0	8	5	2	0	15
Totals	2*	54	54	23	2	135
Means	0.3*	5.4	5.4	2.3	0.2	13.6
General Major Hail Day Prob.	0	18%	17%	7%	0	10%

Source: Alberta Hail Studies records

* In 1957, 1958 and 1960, report cards were not sent out before the end of May. Thus these years have been excluded from the compilation of the May values.

[2] The odd report for April and October has been disregarded here because the farmers have not been instructed to report hail outside the period of summer operations at Penhold (mid-May to mid-September). Hail is rare in April and October, but not by any means unknown.

Over the ten years 1957 to 1966, an average of 68.8 hail days per year has been recorded by the network. The high of 80 in 1957 was equalled in 1962 and 1963; 1961 was the quietest year, with only 37 hail days. This was exceptional, however, for the next lowest total is 59, in the year 1960.[3]

Major Hail Days

Table II shows the numbers of major hail days experienced by the project area. A major hail day will be arbitrarily defined here as a date for which fifty or more reports were sent in to Alberta Hail Studies by the observers.[4] May and September are virtually free from major hail days, and the average for August is only 2.3. June and July are the months of maximum hail severity, each averaging 5.4 major days.

The annual totals show a greater relative variation than do the hail day values, ranging from 4 in 1961 and 6 in 1958 to 17 (1962, 1963 and 1965) and 19 (1957). The average is 13.5. The ratio of major days to hail days is highest (about 1:4.5) in the most active years, and diminishes rapidly, so that quieter years such as 1958 and 1961 have a frequency of only 1:9 or 10. It is worth noting that 1960, with 14 major days out of only 59 hail days, is a quiet year simply because May and September recorded no hail. All 59 of its hail days occurred in June, July and August, when the ratio of major to hail days is at its peak, thus resulting in the very high frequency of 1:4.2.

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[3] The distribution of hail days through the season, and the annual totals, may be compared with the figures revealed by hail-reporting networks in other parts of the world. But it must be remembered that hailfall at the ground is an areal phenomenon, and reports received are influenced by the area of the network.

[4] This definition cannot be followed on survey days. It has been found that the running of a survey pre-empts a number of reports which would otherwise have been mailed in. Studies during the 1966 season on comparable storms, some surveyed and some not, in areas of similar population density, suggested that some 15 per cent of the reports obtained by a survey would have been sent in by the observers if no survey had been run. Hence the definition must be modified to: "a day when the number of unsolicited reports, plus 15 per cent of the survey reports, is greater than, or equal to, fifty".

Singularities

Appendix B gives the actual dates of every hail day and major hail day recorded by Alberta Hail Studies. Certain conclusions can be drawn from them regarding singularities, although it must be admitted that these would be far more valuable if the period of observation were longer.

It is interesting to note that only one date, July 15, has been a hail day in each of the ten years. Figure 9 shows the total hail days recorded throughout the period on a given date, together with three-day and eleven-day running means.[5] Figure 10 shows the total numbers of unsolicited reports received over the ten years for each particular date of the hail season. The fluctuations are of course very large. For instance, June 24 has had 1177 reports, while June 23 has had only 151. There are a number of peaks and troughs which the three-day mean does not smooth out. But before identifying any peak singularities, it must be pointed out that the totals are greatly affected by a single day of extreme severity. In 1962, June 10 yielded 588 unsolicited reports, while this date has had hail only five times from 1957 to 1966 and produced a total of only 104 unsolicited reports in all the other years combined. Yet June 10 stands out as a peak singularity in Figure 10. When Figures 9 and 10 are compared, it is seen that many of the peaks and troughs do not coincide. It is extremely hard to identify singularities in hail occurrence with such a short period of record.

Changnon,[6] working on Illinois hail day statistics, used a minimum

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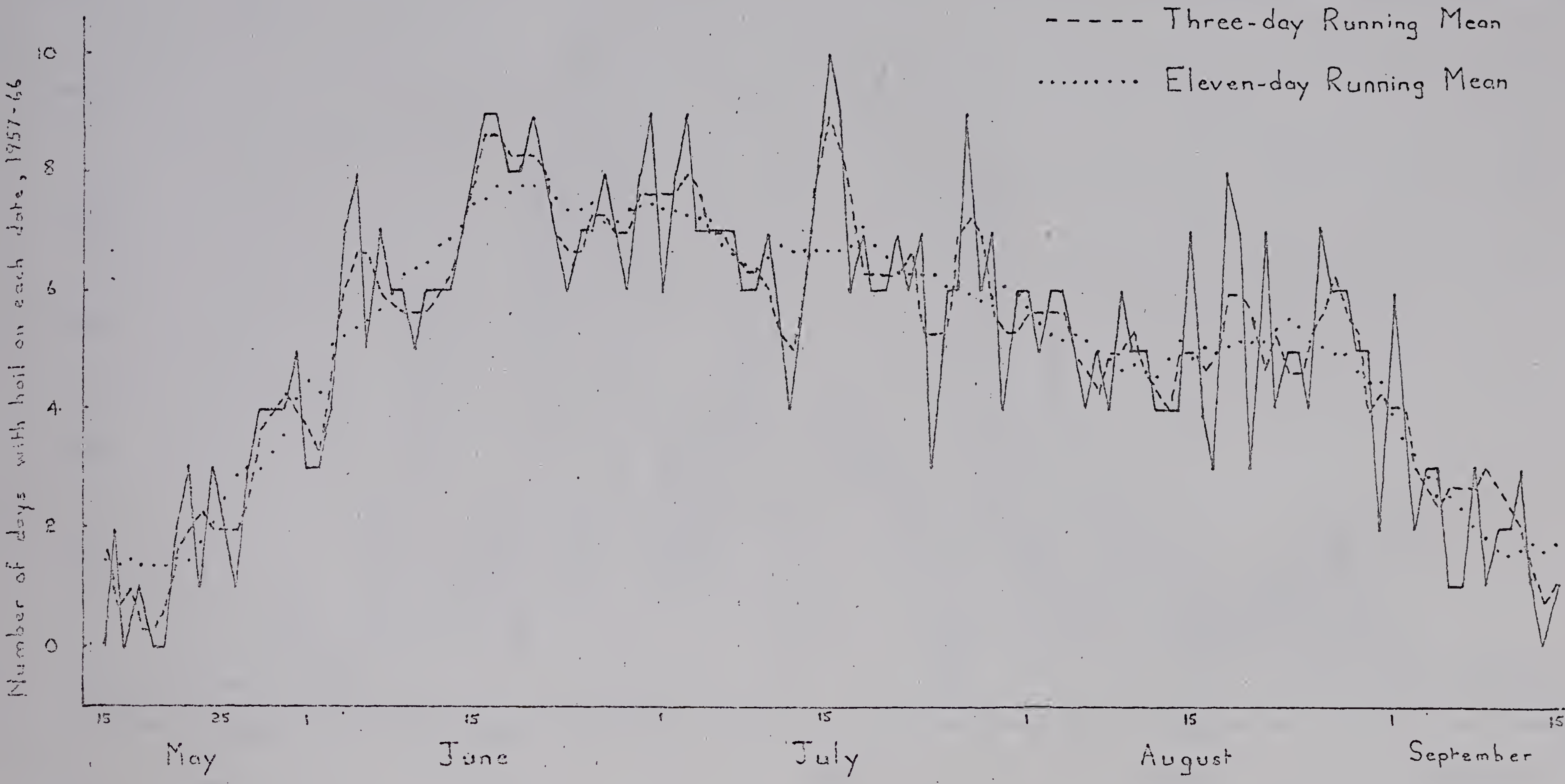
[5] Because of the relative shortness of the Alberta hail season, the eleven-day mean was chosen as a reference to which peaks and troughs could be compared, rather than the average of ten-day consecutive periods used by Changnon in Illinois. Activity in Alberta is usually either distinctly rising or falling over any ten-day stretch, instead of remaining nearly steady.

[6] Changnon, S.A., Jr., Singularities in Severe Weather Events in Illinois, CHIAA Research Report No. 13, Crop-Hail Insurance Actuarial Association, Chicago, October 22, 1962.

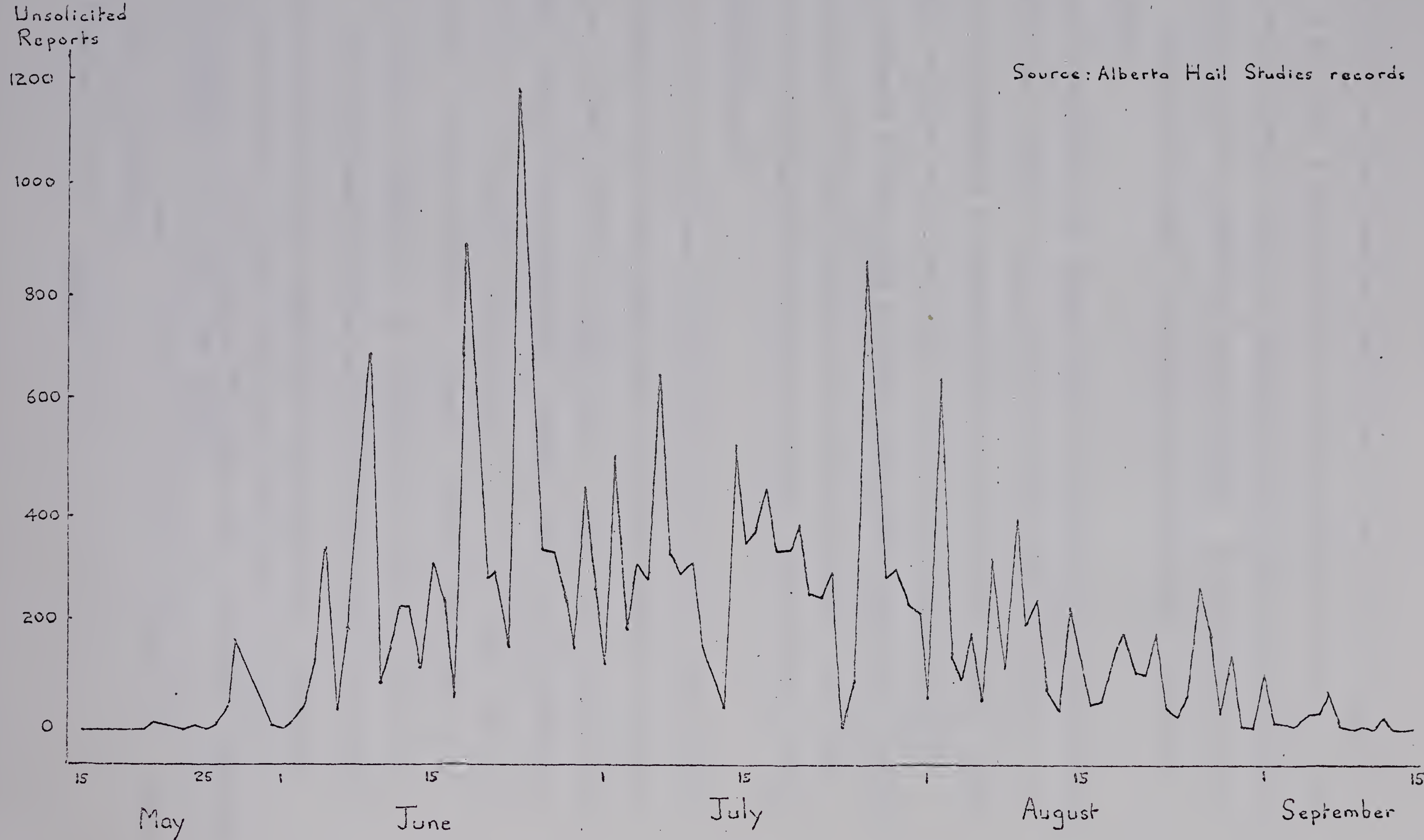
FIGURE 9

HAIL DAYS PER DATE



Source: Alberta Hail Studies records, 1957-66

FIGURE 10 - NUMBERS OF UNSOLICITED REPORTS PER INDIVIDUAL DATE, 1957-66.



variance factor of the three-day running mean of two standard deviations (about 35 per cent; a value of 50 per cent was used by the writer for Alberta data) from the normal to define a singularity, where the normal was taken as the average value for consecutive ten-day periods. He was able to identify various "peaks" and "troughs" in Illinois hail activity over a fifty-nine year period.

The view has been put forward that such singularities in meteorological phenomena have a definite cause and are not merely random occurrences. For instance, singularities in rainfall have been correlated with meteor showers by Bowen,[7] and have been found to have worldwide significance by Brier.[8] Changnon compared Illinois peak hail dates with those experienced in Western Switzerland, and the lack of association led him to conclude that "hail singularities may not show the worldwide agreement found by Brier for rainfall singularities."[9]

If any use is to be made of Alberta Hail Studies data in this context, it is necessary to establish whether any of the peaks apparent in Figures 9 and 10 can be identified over a longer period. Figure 11 was compiled from the damage reports of the Alberta Hail Insurance Board for the twenty-one years 1946-66. It is readily seen that many of the Hail Studies peaks and troughs seem to vanish in Figure 11; however, several of the dates still remain as apparent singularities in hail activity visible in each of the graphs. Since insurance statistics are for the whole province it follows that the singularities can be regarded as being applicable to the whole

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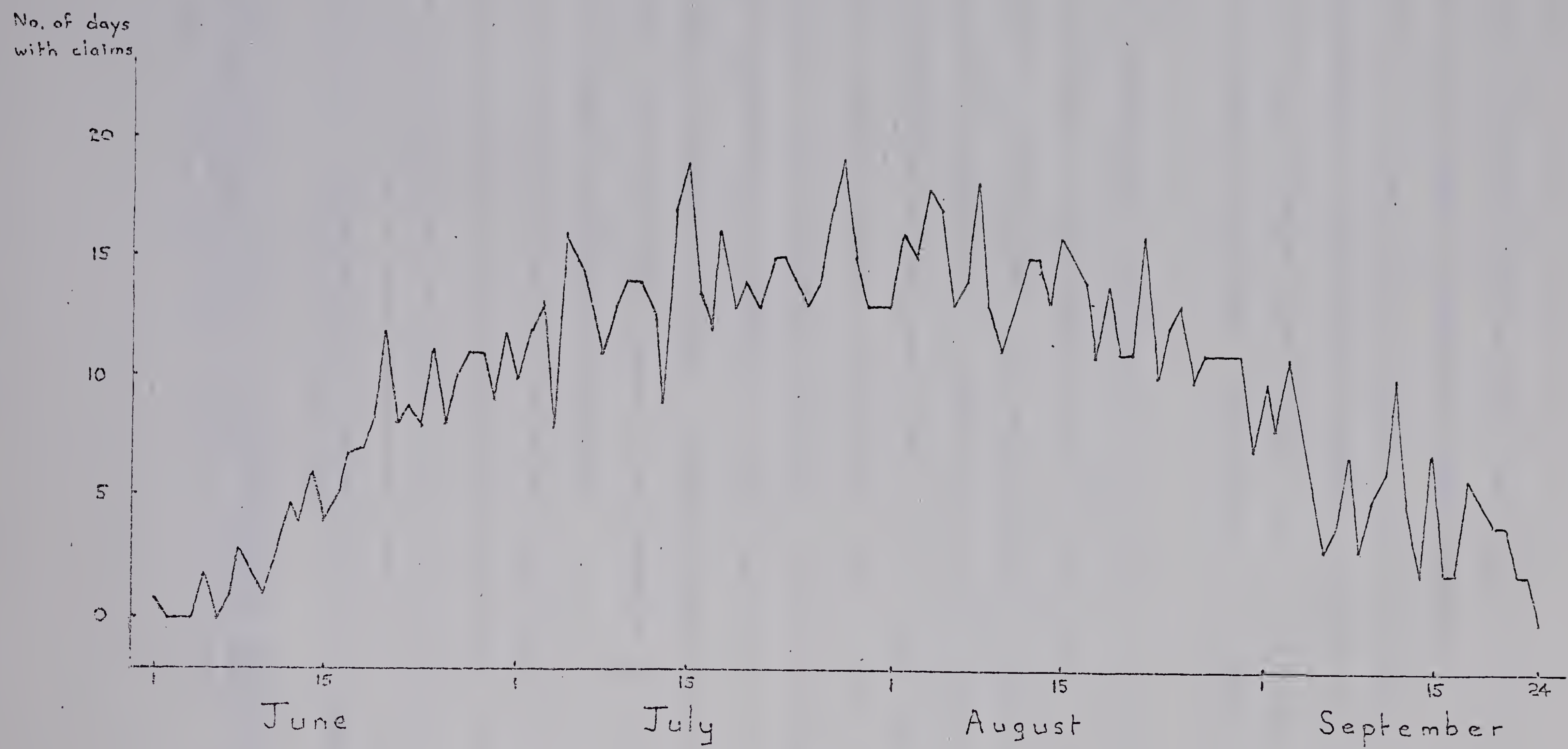
[7] Bowen, E.G., "The Influence of Meteoritic Dust on Rainfall", Australian Journal of Physics, Vol. 6, 1953, pp. 490-497.

[8] Brier, G.W., "A Test of the Reality of Rainfall Singularities", J.Met., Vol. 18, 1961, pp. 242-246.

[9] Changnon, S.A.,Jr., op. cit., p. 7.

FIGURE 11

NUMBER OF DAYS PER DATE WITH DAMAGE CLAIMS RECEIVED BY THE ALBERTA HAIL INSURANCE BOARD, 1946-1966



Source: A.H.I.B. records

province.

July 14-15 is the most significant peak, while August 15, September 1 and September 12 also appear as recognisable peak singularities. Comparison with the dates of hail peaks given in Changnon's paper for Western Switzerland shows a good agreement for July 14-15 and September 12, while the Alberta peaks of August 15 and September 1 are secondary peaks in Switzerland. However, of the Illinois singularities, only September 1 coincides with the Alberta dates.

Beckwith and Schleusener and Grant give actual dates of hail days for Denver and northeastern Colorado respectively.[10,11] But only the former presents data for a number of years. All Denver network hail days from April 1949 to October 1955 are given, but it appears that the peak singularities, if these are identifiable in seven years of data from the small Denver network, do not agree with those in Alberta or Switzerland. May 15, June 6, June 27, July 27 and August 3 show up as peak singularities. There is no correlation between these and Switzerland or Alberta, but June 6 and July 27 are visible as peaks in Changnon's graph for Illinois. Three more peaks may be identified very tentatively. These are July 5, August 27 and September 19, of which only August 27 (in Illinois) is visible in other areas.

There is some doubt in the mind of the writer concerning the real significance of the Illinois hailfall singularities identified by Changnon, since they are all found either very early or late in the hail season. The

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[10] Beckwith, W.B., "Characteristics of Denver Hailstorms", Bull. Amer. Met. Soc., Vol. 38, No. 1, January 1957, pp. 20-30.

[11] Schleusener, R.A., and Grant, L.O., Characteristics of Hailstorms in the Colorado State University Network, 1960-61, Atmospheric Science Technical Paper No. 20, Civil Engineering Section, Colorado State University, Fort Collins, Colorado, October 1961.

general probability of hail on a given day at these times is low. Hence a large percentage variation may not be significant, as it is based on comparison with a small mean value. There appears, however, to be some correlation of hail singularities between Alberta and Switzerland, and between the Denver network and Illinois, but there is no correlation between the two groups.

Maybank and Qureshi have studied rainfall singularities on the Canadian prairies and suggested that they do not support the view of Bowen.[12] The Alberta hailfall peaks do not correlate with prairie rainfall peaks (only July 15 shows up, as a very minor peak), but like rainfall they too show no definite association with known meteor showers, even when various "delay periods" are considered.[13]

Even if the criticism of Changnon is valid, there is a basis, considering only Switzerland, Denver, Illinois and Alberta, for the suggestion that hail singularities are not as widely experienced as might be anticipated from the meteor shower theory. Hail in mid-latitudes is largely a summer phenomenon, and thus its singularities cannot be expected to be the same in the two Hemispheres.

In conclusion, however, Alberta hailfall data do suggest that the theory proposed by Bowen to explain rainfall peak singularities is inapplicable to dates of recurring hail activity.

Hail Day Associations

One striking feature of Appendix B is the tendency

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[12] Maybank, J., and Qureshi, M.M., "An Alternative Explanation of Rainfall Anomalies", J. Atm. Sci., Vol. 23, No. 1, January 1966, pp. 13-24.

[13] The "delay period" is the time required for the meteoritic dust to settle through the stratosphere before its effects are felt in the troposphere. Delays of 30, 42 and 60 days were applied to the meteor shower dates given by Maybank & Qureshi, in an attempt to fit the Alberta hail peaks.

towards clustering, both of hail days and non-hail days, and especially the proximity of major hail days to one another. Appendix C is a summary of hail day probability following specific situations on the previous day (Part 1) and on the previous two days (Part 2). It is based on analysis of actual past occurrences. Although it would be interesting to carry this analysis still further, i.e. by considering fourth-day probabilities given the state of affairs for the previous three days, and so on, the value would be seriously limited by the scarcity of past experience.

There has been interest in similar analyses referred to rainfall and the occurrence of wet and dry spells. For instance, Longley has worked on Canadian data,[14] while Lawrence has examined persistence at English rainfall stations.[15] In Israel, Gabriel and Neumann have developed a model for the explanation of daily rainfall at Tel Aviv.[16] It is but a short step to extend the discussion of the persistence of rainfall at a point to the persistence of hailfall over an area.

Table III is an extract of some of the more important statistics listed in Appendix C. When the general or expected probabilities (Table I) are set aside actual observed values given the prior situation, it seems reasonable to conclude that one hail day tends to be followed by another, particularly where major hail is involved. A few instances might be cited:

(i) The probability of a hail day following another is 71 per cent between June 1 and August 31; this compares favourably with an expected

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[14] Longley, R.W., "The Length of Dry and Wet Periods", Quart. J. Roy. Met. Soc., Vol. 79, No. 342, October 1953, pp. 520-527.

[15] Lawrence, E.N., "Application of Mathematical Series to the Frequency of Weather Spells", Met. Mag., Vol. 83, No. 985, July 1954, pp. 195-200.

[16] Gabriel, K.R., and Neumann, J., "A Markov Chain Model for Daily Rainfall Occurrence at Tel Aviv", Quart. J. Roy. Met. Soc., Vol. 88, No. 375, January 1962, pp. 90-95.

TABLE III - EXTRACT OF SIGNIFICANT HAIL DAY PROBABILITIES

	Probability for Next Day (%)											
	June & July				August				June 1 - Aug. 31			
Previous Situation	HD	MHD	NHD	# of Cases	HD	MHD	NHD	# of Cases	HD	MHD	NHD	# of Cases
2 Cons HD	74	22	26	301	60	7	40	96	71	18	29	397
1 HD	75	23	25	404	61	11	39	157	71	19	29	561
2 NHD	52	7	48	103	35	5	65	87	45	7	55	190
1 NHD	53	9	47	204	41	5	59	152	48	7	52	356
2 MHD	90	19	10	31	100	0	0	3	91	18	9	34
1 MHD	86	29	14	108	74	13	26	23	84	26	16	131
2 LHD	66	18	34	150	60	5	40	65	64	13	36	215
1 LHD	70	20	30	296	58	10	42	134	67	17	33	430
2 HD (1M)	84	25	16	182	65	12	35	34	81	23	19	216
NHD, HD	68	18	32	204	55	10	45	126	61	15	39	330
Expected Prob.*	67	18	33		51	7	49		61	14	39	

2 Cons HD = 2 consecutive Hail Days

HD = Any Hail Day

MHD = Major Hail Day

NHD = No-hail Day

2 HD (1M) = 2 consecutive Hail Days, one of them Major

NHD, HD = 1 No-hail Day and 1 Hail Day, in either order

LHD = Minor Hail Day

* These figures are simply the observed hail day probabilities. For example, during the ten months of August in which the project has been operating, 51 per cent of the days have had hail, 7 per cent have had major hail, and 49 per cent have had no hail.

Source: Alberta Hail Studies records

value of around 61 per cent. Even in June and July, when the expected probability of any day having hail is high (67 per cent), the value actually experienced is still higher, at 75 per cent.

(ii) The probability of a hail day following two consecutive days with hail in this period is 71 per cent also (a value of around 61 per cent would be expected); if one or more of the first two days is major, the actual probability of hail in the network on the third day rises to 82 per cent.

(iii) The June 1-August 31 probability of a day with no hail after a similar day is 52 per cent, compared with an expected 39 per cent. Even in June and July, when the probability of any given day having no hail is as low as 33 per cent, the actual value for the day after a no-hail day is 47 per cent.

(iv) The June 1-August 31 probability of a third no-hail day following two such days is 55 per cent (cf. an expected value of around 39 per cent).

It is likely that the reason for these associations is to be found in the synoptic situation rather than in sheer randomness; a state of affairs favourable to hailfall may persist for a while and then fade away. No more hail is recorded until another suitable local synoptic situation has developed. However, without a detailed consideration of the synoptic meteorology of the various hail seasons, which is beyond the scope of the present study, no such assertions can be substantiated.

At first sight it appears that Appendix C and Table III could be a great aid to the forecasting of hail in the project area. But in fact this is not feasible, at the present time anyway, for it may not be known for days afterwards whether a given date was a minor or major hail day or a no-hail day.

Persistence of Hail in Central Alberta

A statistical measure of the affinity of one hail day for another is "persistence". Besson has developed a Coefficient of Persistence[17] which can easily be applied to "runs" of hail days:

$$R_B = \frac{1 - p}{1 - p'} - 1$$

where R_B is Besson's Coefficient of Persistence,

p is the general probability of a hail day, and

p' is the probability of a hail day if there was hail on the preceding day.

From this coefficient of persistence, which is not widely used, a further coefficient r_B,[18] comparable to a correlation coefficient, may be derived by putting

$$r_B = 1 - \left[\frac{1}{R_B + 1} \right]^2 .$$

Hence the value of r_B is given by:

$$r_B = 1 - \left[\frac{1 - p'}{1 - p} \right]^2 .$$

TABLE IV - VALUES OF r_B

Period	p	p'	R_B	r_B
June	0.68	0.77	0.39	0.48
July	0.65	0.73	0.30	0.41
August	0.51	0.61	0.26	0.36
June 1-Aug. 31	0.61	0.71	0.34	0.45

Source: Alberta Hail Studies data

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[17] Brooks, C.E.P., and Carruthers, N., Handbook of Statistical Methods in Meteorology, H.M.S.O., London, 1953, p. 310.

[18] Loc. cit.

Table IV gives the values of r_B for the months of June, July and August, based on all ten hail seasons. May and September are not included because of the paucity of instances from which the coefficient would have to be derived. It will be seen that the values of r_B are quite significant.

Another method of attacking this question of the clustering of hail days is by considering the numbers of runs of one or more hail days in a particular period.[19] If it is assumed that there is no persistence, then the theoretical numbers of runs of one or more, two or more, three or more ....etc. days which could be expected are given by:

$$Nqp,\ Nqp^2,\ Nqp^3 \ldots\text{etc.},$$

where N = total number of days in period,

p = general probability of a hail day, and

q = 1 - p, the general probability of a no-hail day.

Hence

$Nqp - Nqp^2$ = expected number of runs of exactly one hail day,

$Nqp^2 - Nqp^3$ = expected number of runs of exactly two hail days, etc.

Table V compares the overall expected and actual frequencies of runs of hail days of various lengths for the ten seasons (the season is defined as May 15-September 15 inclusive).[20] A χ^2 test was applied to the data and a value of 127.6 was obtained for χ^2. With twelve degrees of freedom, this is highly significant statistically at the 0.001 level. Since the deviation of actual from expected runs is negative for small values of n, and positive for large values, the view that hail is a feature showing a marked degree of persistence is well supported by the test. It is interesting to note, however, that the cumulative totals of observed runs of hail days approximate to a logarithmic relationship (Figure 12) similar to that

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[19] Ibid, pp. 310-312.

[20] For the compilation of Table V, see Appendix D.

FIGURE 12

CUMULATIVE TOTALS, RUNS OF n HAIL DAYS

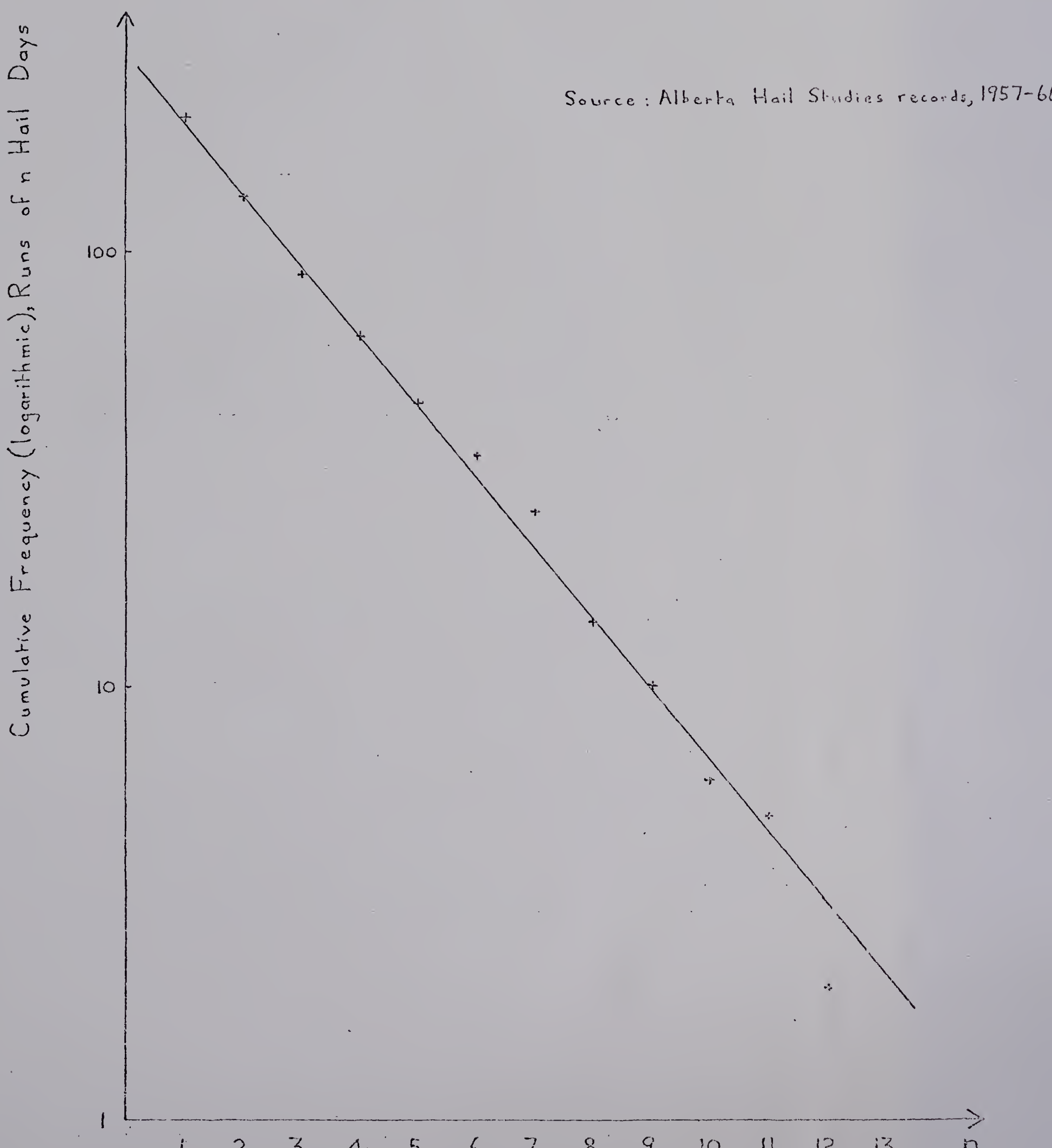

TABLE V - EXPECTED AND ACTUAL RUNS OF HAIL DAYS

n	Expected no. of runs of n hail days E	Actual no. of runs of n hail days A	A - E	$\frac{(A-E)^2}{E}$
1	147.3	69	-78.3	43.0
2	72.6	44	-28.6	11.3
3	37.0	25	-12.0	3.9
4	19.7	19	- 0.7	0.0
5	10.5	11	0.5	0.0
6	5.8	9	3.2	1.8
7	3.1	11	7.9	20.1
8	1.8	4	2.2	2.7
9	1.0	4	3.0	9.0
10	0.6	1	0.4	0.2
11	0.3	3	2.7	24.3
12	0.2	1	0.8	3.2
13	0.1	1	0.9	8.1

Degrees of Freedom = 12

$$\chi^2 = \sum \frac{(A-E)^2}{E} = 127.6$$

Source: Alberta Hail Studies data

described by Longley for dry spells at Montreal.[21] Hence if a day has hail the probability of the following day experiencing hail is almost constant regardless of how many consecutive hail days have gone before.

[21] Longley, op. cit., p. 522.

CHAPTER V

UNSOLICITED REPORTS AND HAIL FREQUENCIES

Year-to-Year Variations

The total of unsolicited reports received from the network in any period is a better indicator of the intensity of hail activity than the number of hail days.[1] For this reason summaries have been compiled for each hail season, and Table VI is derived from these. If the problems of varying response are discounted, a picture of the differing severity of the individual years is obtained.

TABLE VI - UNSOLICITED REPORTS BY YEAR

Year	Number of Unsolicited Reports	Year	Number of Unsolicited Reports
1957	3221	1962	3613
1958	918	1963	3307
1959	3355	1964	2012
1960	2878	1965	2118
1961	647	1966	2158
	Total 24,227		Mean 2,423

Source: Alberta Hail Studies records

The broad view is the same as that given in Table I for network hail day totals, but is perhaps a little more revealing.

Seasonal Variations

Table VII gives the total numbers of unsolicited reports

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[1] One report for any date is sufficient to make it a "hail day". The total of unsolicited reports received also gives some indication of the areal extent of activity.

received over the ten years by months. This analysis was performed by the examination of summaries.

TABLE VII - UNSOLICITED REPORTS BY MONTH OF YEAR

	May	June	July	Aug.	Sept.
Total of Unsolicited Reports	484	8,968	9,672	4,725	378
Average Number per Day	2*	30	31	15	1

* May reports are regarded as being derived from seven years only, and the mean is calculated on this basis. Even so, it is virtually arrived at from the period May 15-31, for the hail report cards are not sent out before May 15.

Source: Alberta Hail Studies records

This gives an idea of the relative intensity of hail activity during the season. July, June and August are the three most active months, in that order, with averages of 31, 30 and 15 unsolicited reports per day respectively; this contrasts with the corresponding hail day probabilities of 66, 68 and 51 per cent respectively. Although June has the most hail days, the average day in July yields more unsolicited reports. An August hail day is more than 75 per cent as likely as a July hail day, yet produces only just over half as many unsolicited reports.

Even though May and September have a similar daily average number of reports, hail is probably more common in May. Farmers are more likely to report hailfall in September, which is harvest-time; also, even in the seven years during which May observations have been sent in, the cards have not been sent out to the reporters before the middle of the month.

Spatial Variation

Simple totals of unsolicited reports have been used in this study to provide an indication of the relative severity of hail activity

over different periods of time. To obtain an idea of how hail frequency varies in a spatial sense over the project area, however, some allowance must be made for the varying density of farm population already referred to in Chapter III. The method employed here makes use of the Green Card Index and can thus be quite specific regarding individual areas. Interpolation from a population density map would be less effective.

Green cards were sent out to the 25,000 potential hail observers in the network area in 1963, and those who were prepared to report hail occurrence on their property were asked to fill them in and return them to Alberta Hail Studies. Information contained on the cards included the land location, postal address and telephone number, if any. It seems reasonable to assume that the majority of those who had furnished reports prior to 1963 would return one. From 1963 on, all hail cards received by the project have been checked against the Green Card Index, and all new observers have been added to it. It thus presents a picture of the number of actual observers in each township. Thus, for each of the groupings of Townships and Ranges in the two spatial analyses, the total of unsolicited hail reports over the ten-year period is divided by the number of Green Cards for that district to obtain an index; this will be termed the Frequency Index, and can be used as a rough indicator in comparing hailfall frequency over the area.

It is obvious that some changes in the observing network will have taken place in ten years. Also, survey (the technique was introduced in 1963) as well as unsolicited reports are processed through the Green Card Index. However, less than 20 per cent of the reports received by Alberta Hail Studies from 1957 to 1966 were obtained by the survey method. Bearing in mind the pitfalls of network reporting, the percentage of observers reporting only during surveys may be regarded in this light as being rather

small.[2]

A further refinement to the Frequency Index is possible. In counting the Green Cards for each township, those obtained by telephone survey in 1966 - they are easily identifiable - were disregarded.[3] These persons probably provided only these solicited reports in the 1966 season, and had not previously reported or filled in a Green Card. Therefore they were not volunteer reporters, at least during the period 1957-66 under review, and their elimination means that the Frequency Index becomes more meaningful.[4]

The index represents the average number of times an observer in each particular area has reported hail on his property in the ten years. It has limitations, but some of these, inherent in voluntary network reporting, can be considered uniform throughout the area.[5] The Frequency Index may still be used, then, in regional comparison, despite the fact that its value does not represent the true frequency of hail on a quarter-section occupied by a volunteer observer. It is likely to be a considerable under-

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[2] Reasons for this conclusion are:

(a) The same region may have been surveyed on several occasions;

(b) Survey reports may well be obtained from those who have made unsolicited reports in the past;

(c) An observer whose first report to Alberta Hail Studies is in a survey may then begin to send in his own reports.

[3] A new method of surveying from large-scale telephone maps was used in 1966 for the first time. It possesses the potential of reaching every single telephone subscriber within the project area if necessary.

[4] The total number of Green Cards after the 1966 season was around 8,700. Of these, about 1,150 were from 1966 telephone surveys, leaving some 7,550 used in the analysis of this chapter. Carte's estimate of a response of 29 per cent suggests that 7,000 of the cards refer to people who do volunteer reports; the probable error in the calculated Frequency Indices is thus 550 in 7,550 or 7 per cent.

[5] Two examples are the inability to report all hail, and the varying reliability of reporters.

estimate.[6]

On this premise, Figure 13 is based on the calculated Frequency Indices for the 122 regional analysis units described in Chapter III. Some major trends are immediately evident. There is a sharp decrease from west to east, values of 4.0 and over being widely encountered in the western sections of the project area. The prairie region in the east, on the other hand, has values consistently less than 2.0. The only extensive areas where the Frequency Index exceeds 5.0 are in the southwest, particularly the foothill country south of Calgary where values of over 6.0 are experienced. The extreme north of the project area has low Frequency Indices. However, a large, roughly triangular tract with Caroline, Bashaw and Buck Lake at the corners has values in excess of 3.0 (the average for the whole project area is 2.8); so a south-north trend is not readily apparent. The existence of small "pockets" of low or high Frequency Index is another feature of the map, but the index itself is not sufficiently accurate to allow any significance to be attached to these.

This analysis confirms the view that hailstorms in Central Alberta commonly form over the foothills and move eastwards.[7] In general, the land closest to the mountains thus receives hail more often than other sections of the project area. The exceptions in the foothills country visible in Figure 13 are worth a mention here, since they comprise the Bearberry-Sundre and Cochrane-Jumping Pound regions. Both straddle the valleys of major rivers, the Red Deer and the Bow respectively, near their exits from the mountains. Yet it has been suggested that the larger valleys in the foothills

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[6] See Paul, A.H., "The Development of Investigation Into Hail Occurrence in Alberta", The Albertan Geographer, No. 3, 1966-67, pp. 4-10.

[7] This point is expanded in Chapter VI. See also Figure 1a for observed hailstorm tracks in the area.

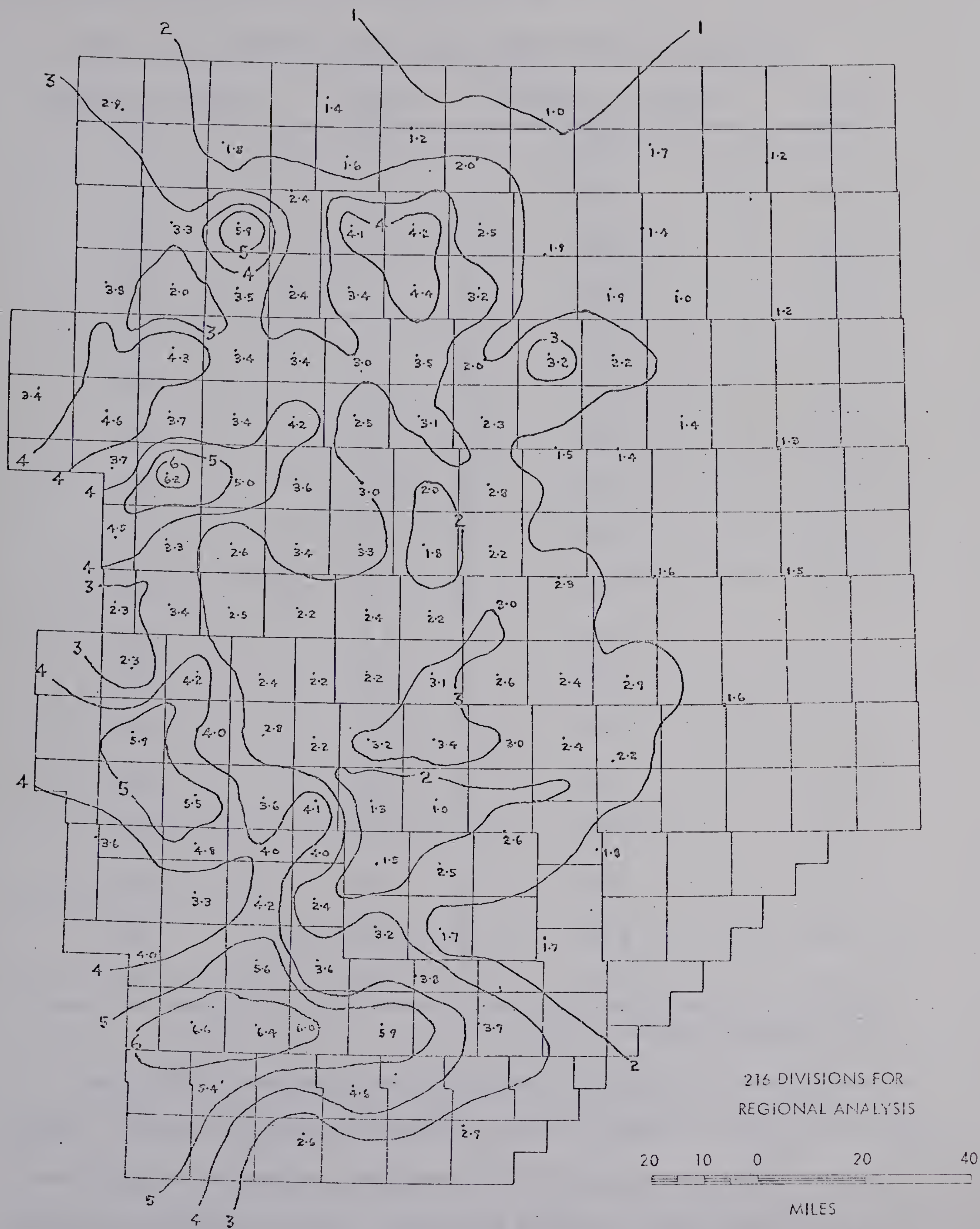

FIGURE 13 – 1957-66 HAIL FREQUENCY INDICES IN CENTRAL ALBERTA

may often be the source of convective storms.

TABLE VIII - FREQUENCY INDEX AND DISTANCE FROM THE MOUNTAINS

Distance in miles	Index	Distance in miles	Index
33	5.6	125	2.7
40	4.8	130	2.4
45	4.8	135	2.8
50	4.7	140	2.4
55	4.2	145	2.7
60	4.8	150	3.1
65	4.5	155	2.3
70	3.2	160	1.8
75	3.7	165	1.7
80	3.6	170	1.8
85	3.0	175	1.5
90	2.7	180	1.6
95	2.9	185	1.2
100	3.3	190	1.2
105	2.8	195	1.3
110	2.7	200	1.4
115	3.1	205	1.2
120	3.2	218	1.1

Source: Computer analysis, 1967

Table VIII is derived from the computer analysis of distance from the Divide. Totals of unsolicited reports were extracted for each of the forty-seven distance categories; the Green Cards for each were summed and the Frequency Indices worked out in the same fashion as above and presented in the table. The decline with increasing distance from the mountains is marked and convincing.

CHAPTER VI

ONSET TIME OF HAIL

Reported onset times are given to the nearest minute. The bias of observers towards the quarters of the hour in stating onset times has already been mentioned. Figure 14a is a reproduction of a diagram given by Douglas showing this,[1] and it is seen that the probable error is reduced to a minimum by the use of the boundaries adoped in this study. Onset times are sorted into classes of fifteen minutes, with the boundaries $7\frac{1}{2}$ and $22\frac{1}{2}$ minutes past the hour, and $22\frac{1}{2}$ and $7\frac{1}{2}$ minutes before the hour (Figure 14b). For greater clarity, many of the data discussed in this chapter are grouped into hours. This eliminates what bias still remains in the quarter-hour analysis, and also simplifies the results. The dividing-line is taken at $22\frac{1}{2}$ minutes past the hour.[2]

The number of cards on which onset time is not stated is small, so that in general sampling problems are not found in dealing with this variable, except in some divisions of the regional analysis. A summary of the data on which this chapter is based is to be found in Appendix F.

Year-to-Year Variation

Figure 15 consists of a series of ten histograms, each showing the percentage frequency of hail onset time by hour of the day -

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[1] Douglas, R.H., The Study of an Alberta Hailstorm, Stormy Weather Research Group, Scientific Report MW-35, McGill University, Montreal, December 1961, p. 1.

[2] Temporal analysis has the same problem as regional analysis in boundary definition and choice of class intervals. Here, the boundary was chosen, as far as possible, to eliminate bias on the part of the observers. However, $22\frac{1}{2}$ minutes before the hour would have served just as well; and ideally the analysis should be performed with varying time intervals to see if these affect the result.

[after Douglas]

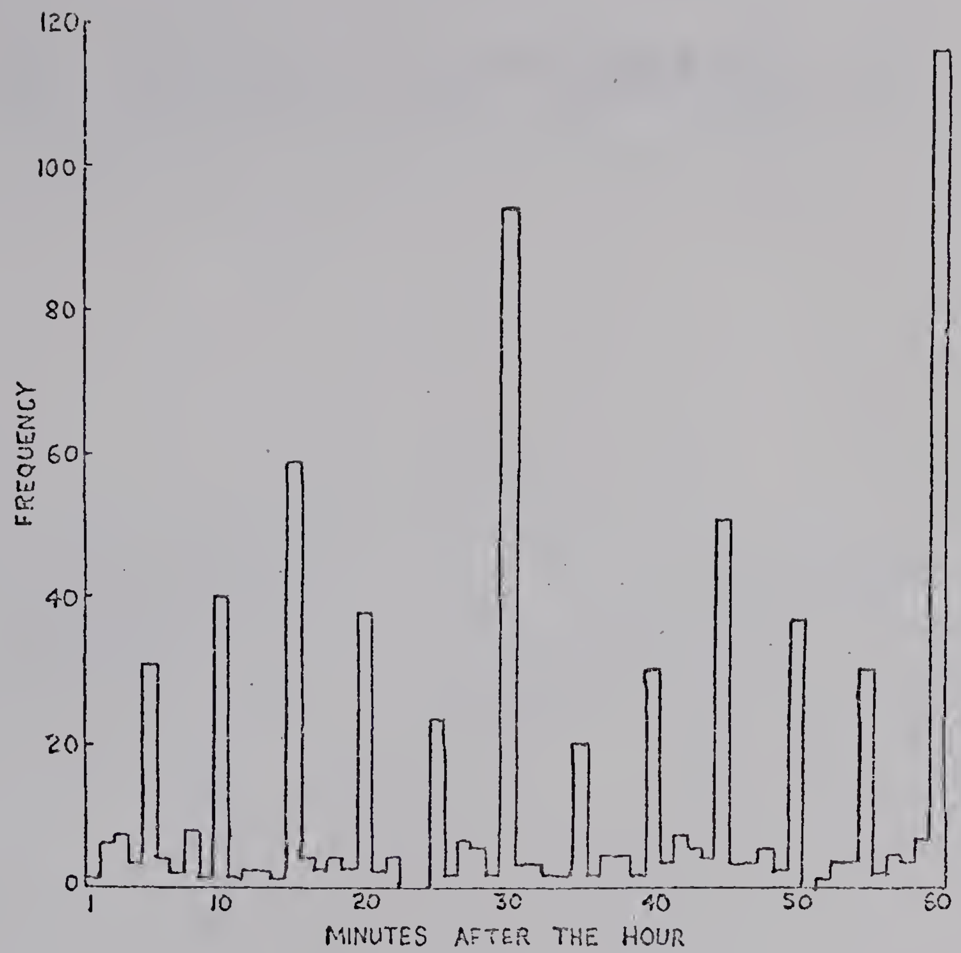


FIGURE 14a – FREQUENCY DISTRIBUTION OF REPORTED HAIL ONSET TIME IN MINUTES PAST THE HOUR

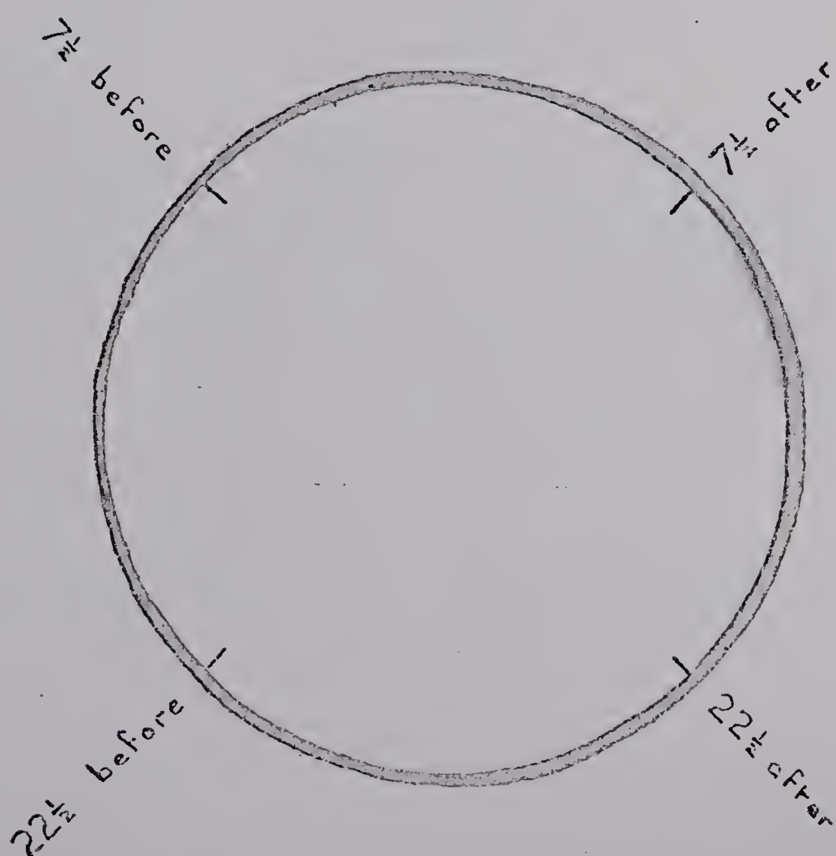
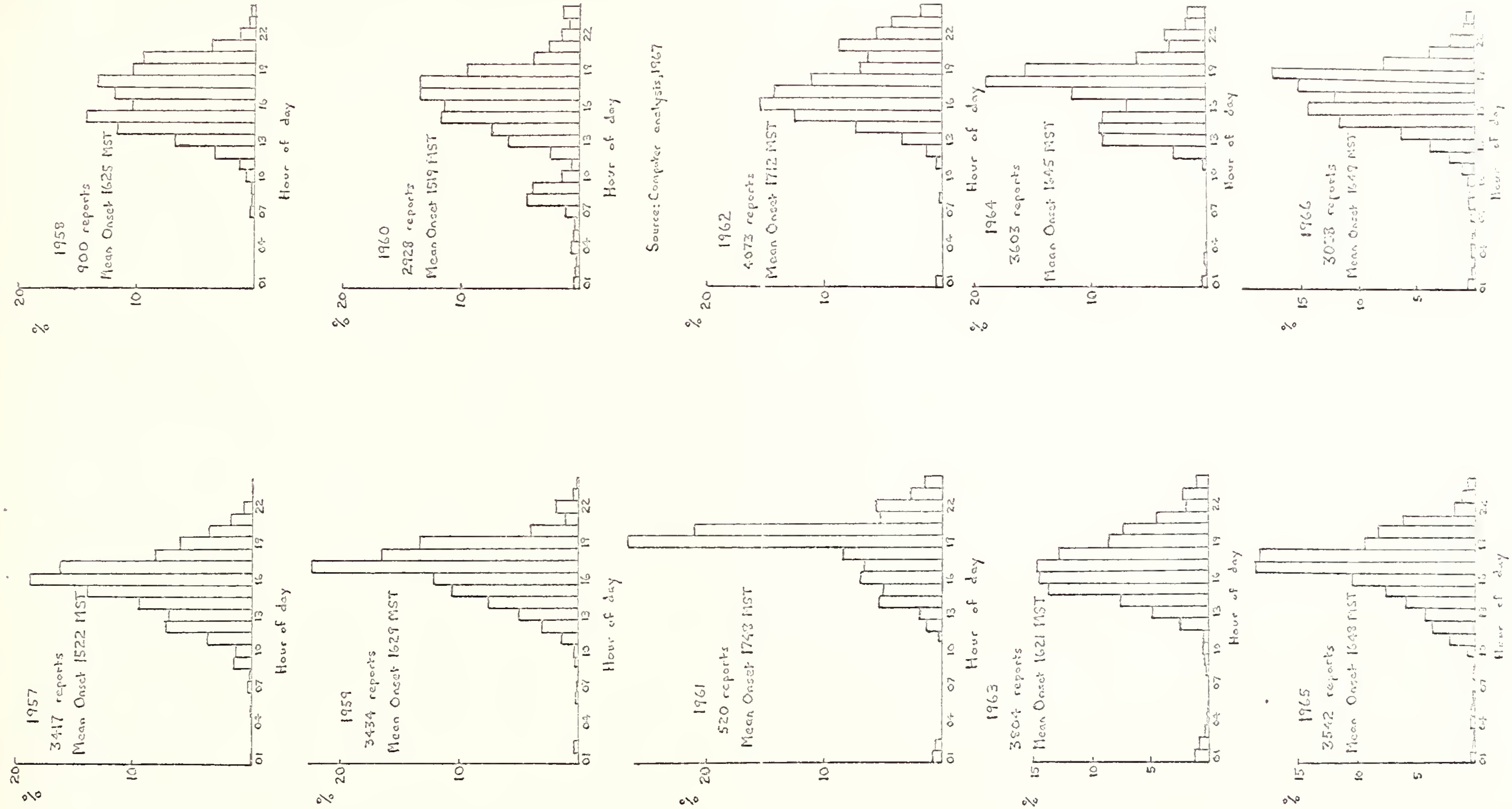


FIGURE 14b – TIME-SORTING BY COMPUTER

FIGURE 15 - YEARLY HISTOGRAMS OF HAIL ONSET



hour "01" refers to hailfall starting between 0023 and 0122 MST - for all the reports of a given year. There is obviously a bias in favour of reporting day-time hail; also, night storms are never surveyed, of course. It is felt, however, that this bias is only slight, since so little hail is experienced at night.

Differences in the form of the histogram are clearly visible. The picture of a wide band of hail activity in afternoon and early evening is general, but the peak may be either broad (for example, 1960 and 1963) or narrow (1959 and 1961), and nocturnal activity is much more marked in some years than in others. Compare, for instance, 1960 with 1959, both above-average years in terms of unsolicited reports, and both without surveys; or 1965, a below-average year with a great many survey reports causing an apparent diminution in the relative frequency of night-time hail, with 1962, a very heavy year, but one with few surveys and virtually no night-time storms reported.

The severity of the year does not seem to be related to these variations. Figure 16 is a diagram showing mean onset time - derived by the computer - with percentage of large hail, and the numbers of unsolicited reports and hail days for each year. There appears to be no good fit. It may well simply be that the relatively rare synoptic situations leading to night-time hailfall have occurred in some years but have been almost non-existent in others.

Seasonal Variation

The cards of all months of May, all months of June, etc., were subjected to analysis here, and Figure 17a gives histograms of onset time percentage frequency by hour for each month of the year. Mean onset times were also calculated by the computer.

An overall seasonal trend is discernible. In May and June the main band of activity is very broad (from around 11 a.m. to 8 p.m.) and the peak of the

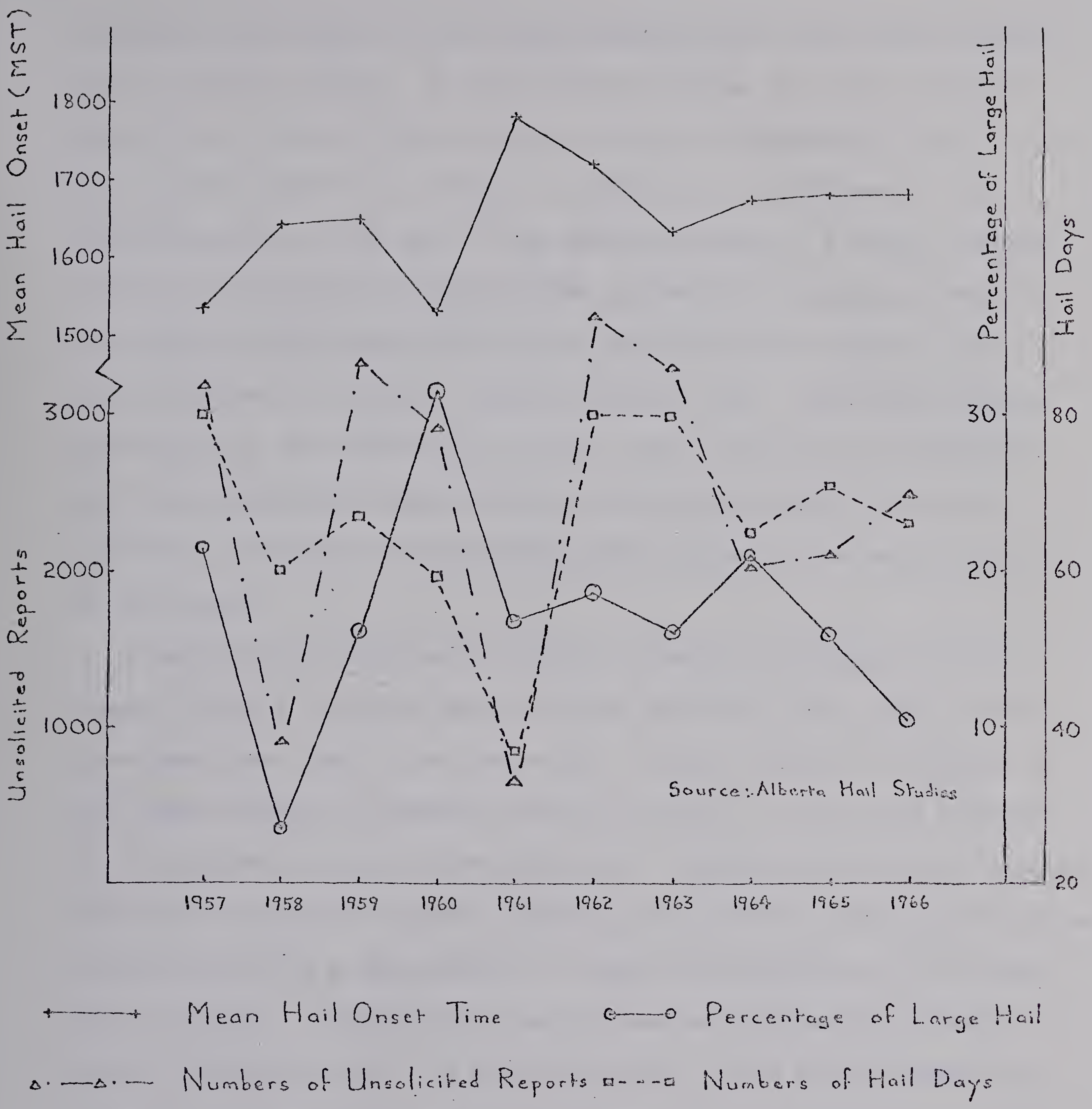


FIGURE 16

A PLOT OF MEAN ONSET TIME, PERCENTAGE OF LARGE HAIL, NUMBERS OF HAIL DAYS AND UNSOLICITED REPORTS BY YEAR, 1957-66.

histogram is not marked. As the season progresses the band becomes narrower and the peak more marked. It also shows some change, the mode occurring at about 5 p.m. in May and 7 p.m. in June, and then retrogressing through 6 p.m. in July and 5 p.m. in August to around 3 p.m. in September. Its relative position in the band of high activity changes in a similar fashion, so that in June and July hailfall builds up gradually during the afternoon to a climax and then falls off, while in other months the climax is more quickly attained and there is a gradual fall-off then. Night-time reports, particularly in the small hours, are most common in May and June; together with the broader band of high activity, this means that there is a more scattered distribution of hailfall throughout the day in the earlier part of the hail season.

Mean onset time (Figure 17b) exhibits a definite variation over the season. In May it is early, and it becomes later until July, which has the latest mean onset time of the five months. It then reverses its movement so that August hailfall is generally earlier than that of July, while September has the earliest mean hail onset time of all. The graph resembles the seasonal variation of unsolicited reports, suggesting that the more common and widespread is hail activity in a given period, the higher the likelihood of its falling later in the day. Synoptic situations favourable to large-scale activity are most frequent in July, but perhaps the storm clouds need a longer time to develop in these situations than in others. Or, alternatively, new cells may be able to grow later in the day at this time of year than in other months.

Onset Time and Maximum Size of Observed Hail

Since there seems to be a relation of onset time and the degree of hail activity (on a seasonal basis, if not from year to year),it was decided to perform a rough examination of the histogram

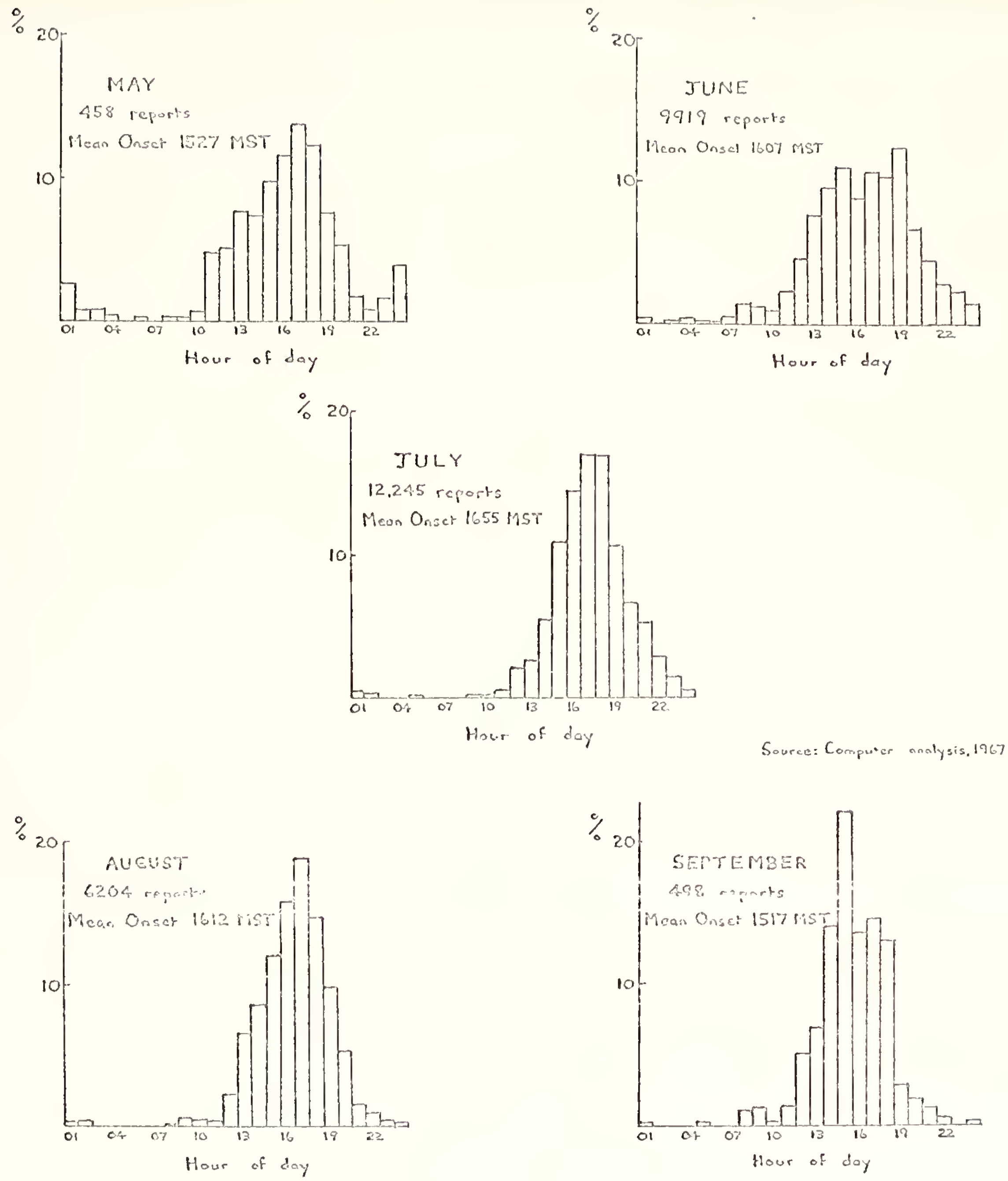


FIGURE 17a - HISTOGRAMS OF REPORTED ONSET TIMES BY MONTH

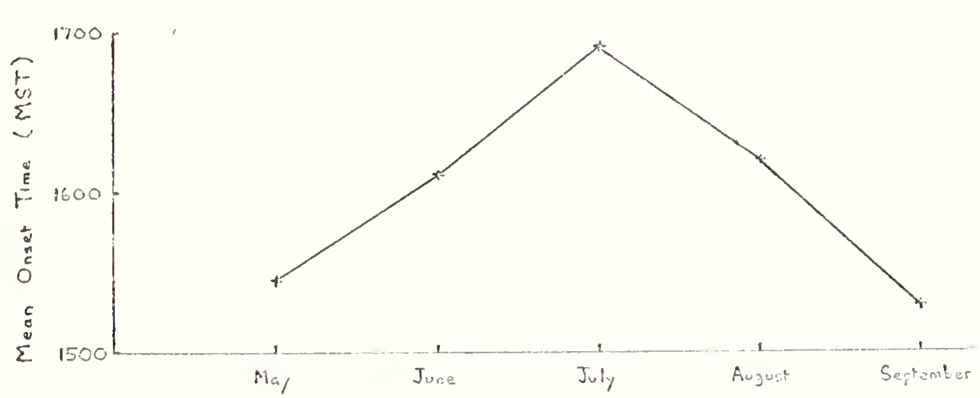


FIGURE 17b - SEASONAL VARIATION OF MEAN ONSET TIME

of onset times for each of the six maximum sizes of observed hail. The relative occurrence of these is also related to hail severity.

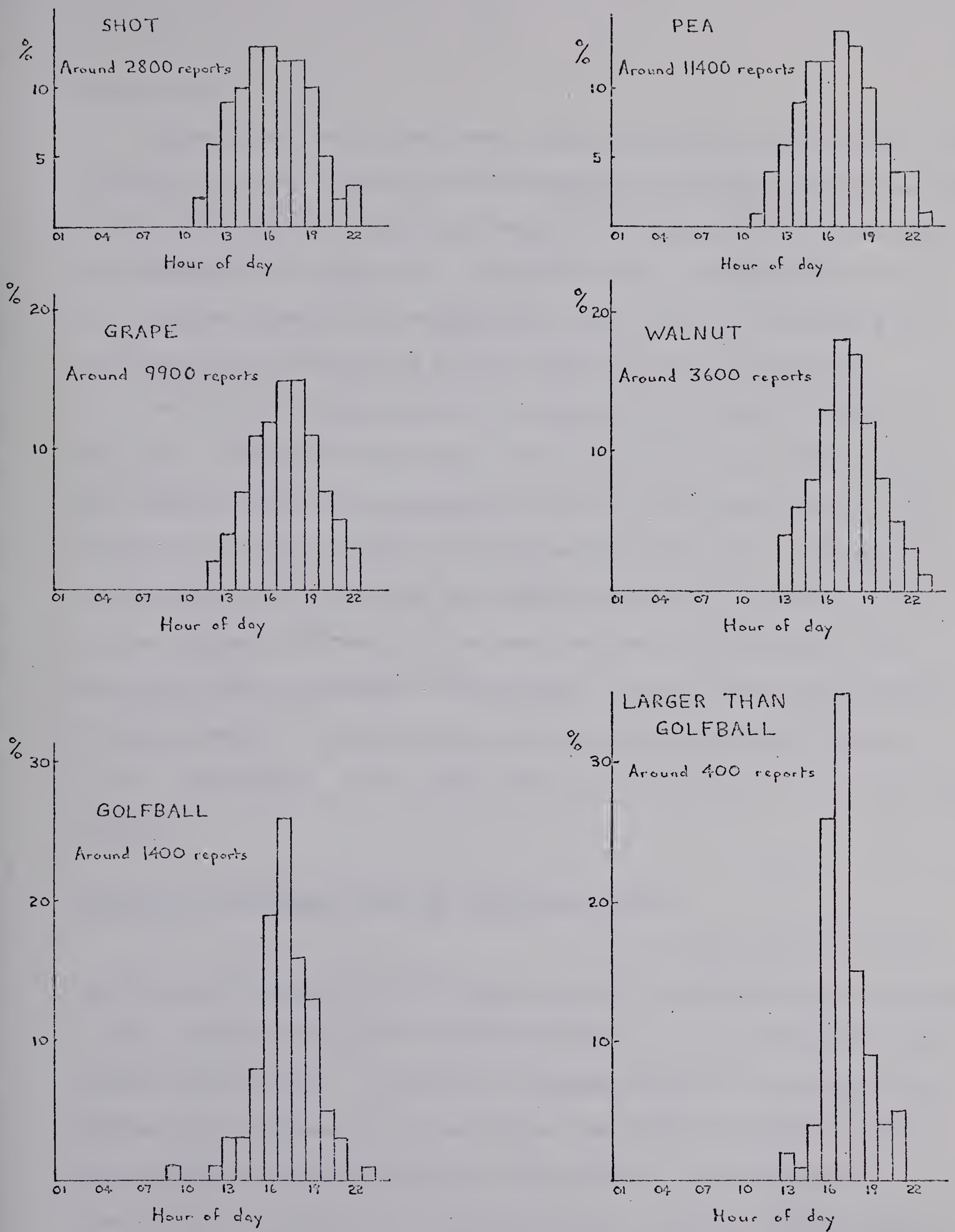
The resulting histograms are given in Figure 18. The analysis was carried only to the nearest whole percent and thus presents an inadequate picture of night-time hail. But it is quite evident that the histogram shows a progressive change with an increase in maximum hail size. The smaller sizes of hail are experienced over a wide range of onset times, with the peak being indistinct. For hail with a maximum size of shot, only 38 per cent of the falls occur in the three hours of highest percentage frequency (1423-1722 hours). All other maximum sizes have the three hours of highest occurrence from 1523 to 1822, and the falls within this range account for 39, 42, 48, 61, and 76 per cent of the totals for maximum sizes of pea, grape, walnut, golfball and larger than golfball respectively.

Thus the largest stones tend to be concentrated into a relatively short period in the late afternoon; hailstorms with smaller stones are the more likely to occur at any time of day, though they too are concentrated, to a lesser extent, into the afternoon and evening.

Spatial Variation

The division of the Analysis Area into 216 small units for regional analysis has been described elsewhere, together with the necessary reduction of these units to 122 in order to maintain a minimum sample of a hundred reports in each grouping.

Again the computer was programmed to output for each of the regional units the percentage frequencies of onset time by quarter-hours and the mean onset time. Since the output of the first part of the programme is somewhat voluminous, it is proposed to deal here only with the variation of Mean



Source: Computer analysis, 1967

FIGURE 18 - HISTOGRAMS OF ONSET TIME FOR THE SIX DIFFERENT MAXIMUM SIZES OF HAIL

Onset Time.[3]

Figure 19 is a map of mean onset times of hail for Central Alberta. The isolines, at hourly intervals, were derived by interpolation between the data points; these are at the geometric centre of the region for which they give the average time of hail onset. In the cases where smaller units have had to be grouped together, the weighted Mean Onset Time for the grouping was calculated from those put out by the computer for the smaller units.

Over much of Central Alberta the average time of onset is between 4 and 5 p.m. There are small pockets which have onset times rather different from those of the areas adjoining them, but the only overall trend at all visible is a delay of hailfall from the southwest (the only sizeable contiguous area of which the most part usually receives hail prior to 4 p.m.) to the northeast, where much of the area receives its hail after 5 p.m. Even this tendency is masked by the presence of areas around Wetaskiwin and to the southeast of Camrose which in general receive their hail before 4 p.m. Nevertheless, it is a real trend and is also evident in the following section.

Variation With Distance From the Continental Divide

Figure 20 is an extract of the mean onset times for the various classes of distance from the mountains - which are approximately at five-mile intervals - with values given to the nearest whole per cent. It shows the expected progression as distance from the mountains increases; it is well known that Alberta hailstorms commonly have a dominant eastward component in their motion. Some fluctuation from one class to the next is naturally present, but the differing degrees

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[3] The output of the former part is stored by Alberta Hail Studies, Research Council of Alberta, Edmonton.

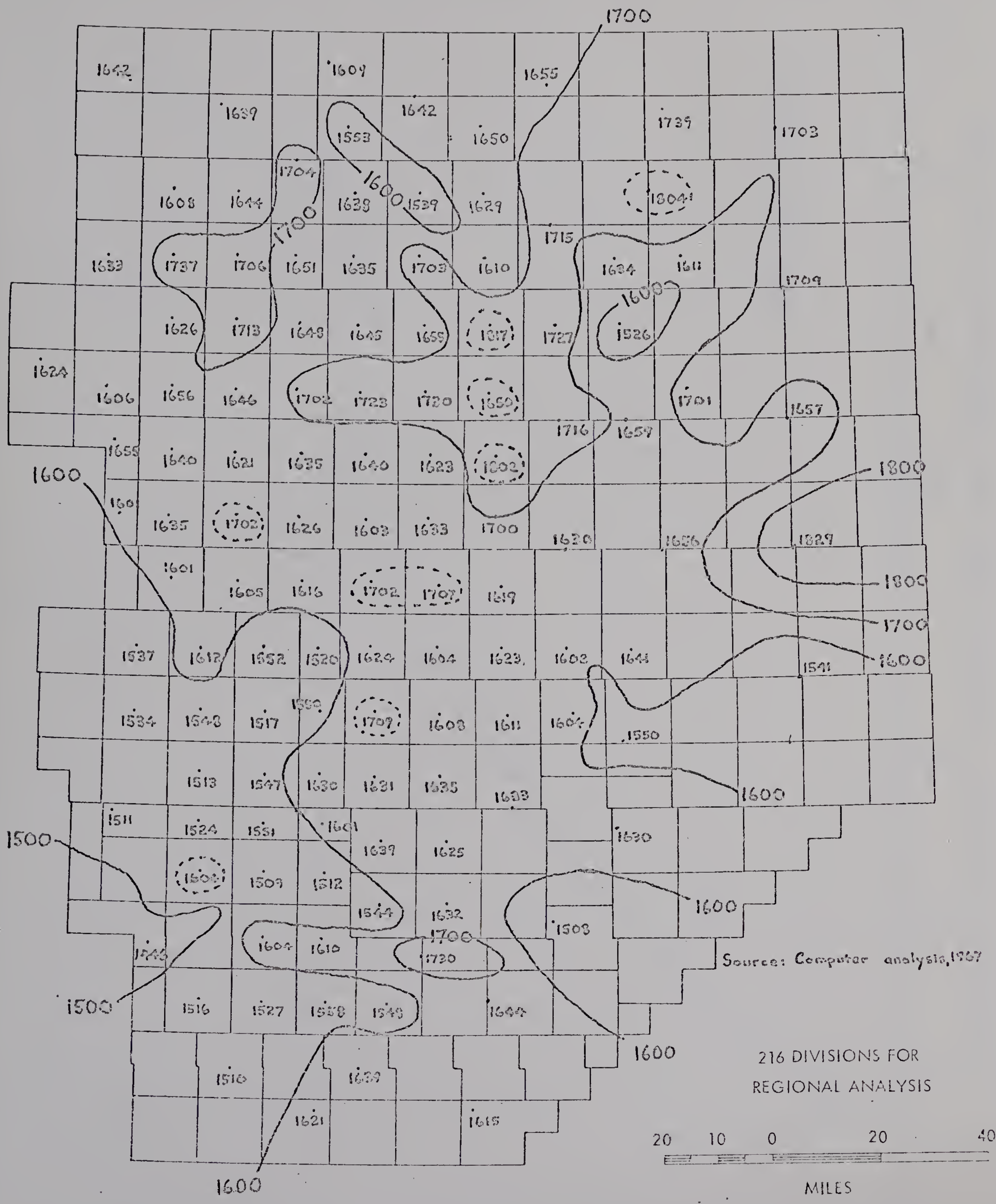
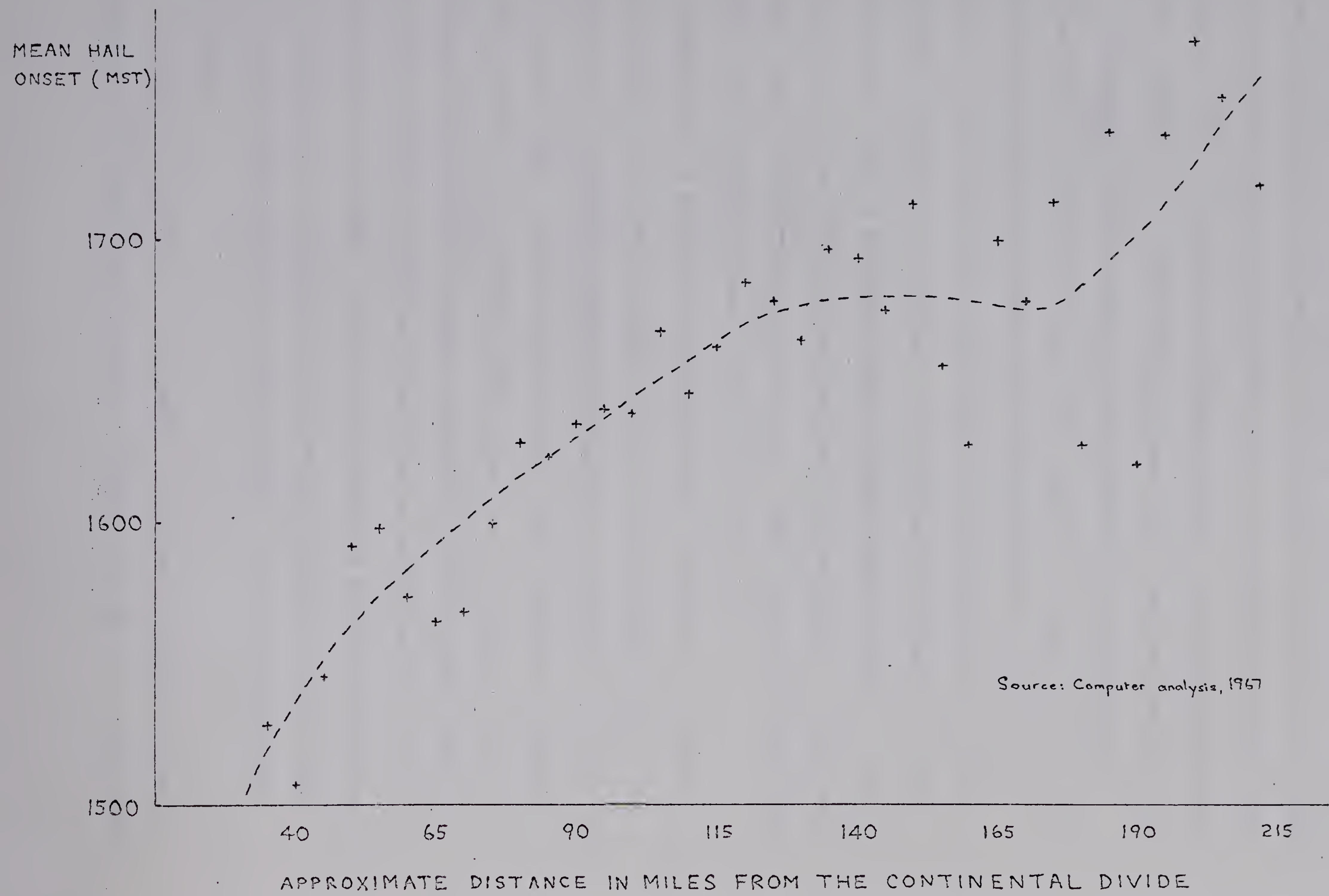


FIGURE 19 - MEAN ONSET TIME (MST) OF HAIL IN CENTRAL ALBERTA, 1957-66

FIGURE 20 - MEAN HAIL ONSET AND DISTANCE FROM THE MOUNTAINS



of this shown by the two parts of the graph are quite striking. There is a marked discontinuity in the region of 120-140 miles. Also around this point, the curve drawn by eye as a rough "best fit" to the scatter of points shows a change in form. Its gradient decreases abruptly, and the right-hand half of the curve has a far smaller change in mean onset time than the left-hand.

The original computer output (in which onset time is divided into quarter-hours as outlined in Chapter III), yields the reason for this. The main period of activity at 40-65 miles from the Rockies is from roughly 11 a.m. to 8 p.m.; apart from a few storms in the vicinity of 9-9:30 a.m. and close to midnight, hail appears to be received at virtually no other time of day. There is a gradual change through Classes 112-120, so that in the latter of these, 100-110 miles from the Rocky Mountains, the main band of hail onset is from around noon to 10 p.m. Apart from some activity still present around midnight, there is virtually no other hail.

Upwards of 115 miles out a secondary "wave" of activity is evident in the early morning. Its onset is around 7:30 a.m. at its closest point to the mountains and is gradually delayed northeastward to 9-9:30 a.m. 175-190 miles from the main range. Another occurs at about 10:30 - 11:00 a.m. from 140 to 200 miles from the mountains. There appears to be no delay in its onset as distance from mountains increases, suggesting that the storms making up this "wave" originate at the same time of day at various points from 140 to 200 miles from the Rockies. Besides this there is a growing tendency for the high activity band to merge with the storms near midnight and even "spill over" into the early hours of the next morning, 165 and more miles from the Rockies.

So there is no doubt that the greater the distance from the mountains, the greater the spread of hail activity throughout the day. For there appear

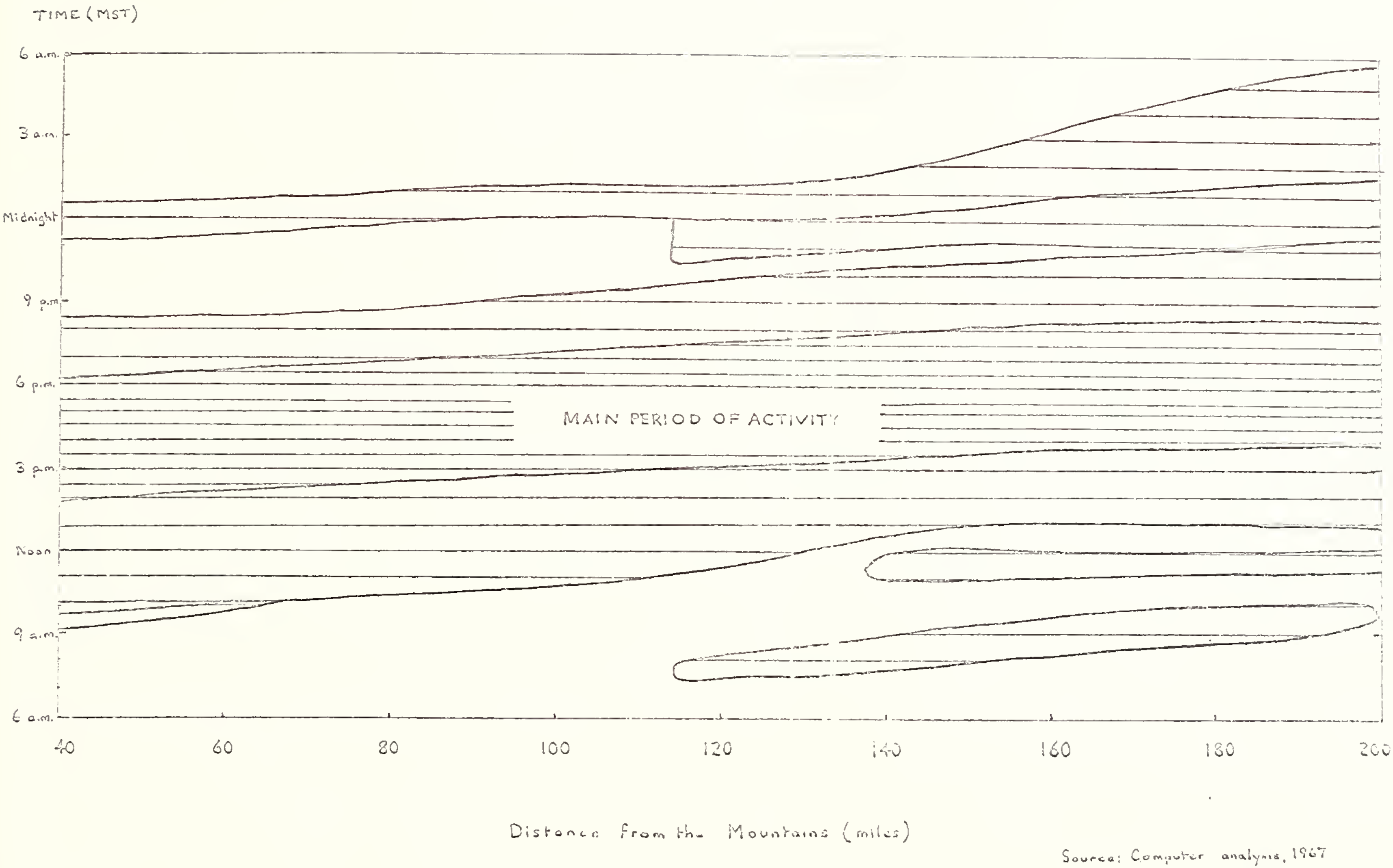


FIGURE 21 - SCHEMATIC DIAGRAM OF HAIL ONSET TIME AS A FUNCTION OF DISTANCE FROM MOUNTAINS

to be three separate "waves" of hailfall during the day, each of some significance, contrasted with only one broad band in those parts of the area closer to the Rockies. Thus, depending on the relative importance of the three waves over the northeastern sections of the project area, larger fluctuations in the mean onset time may exist here.

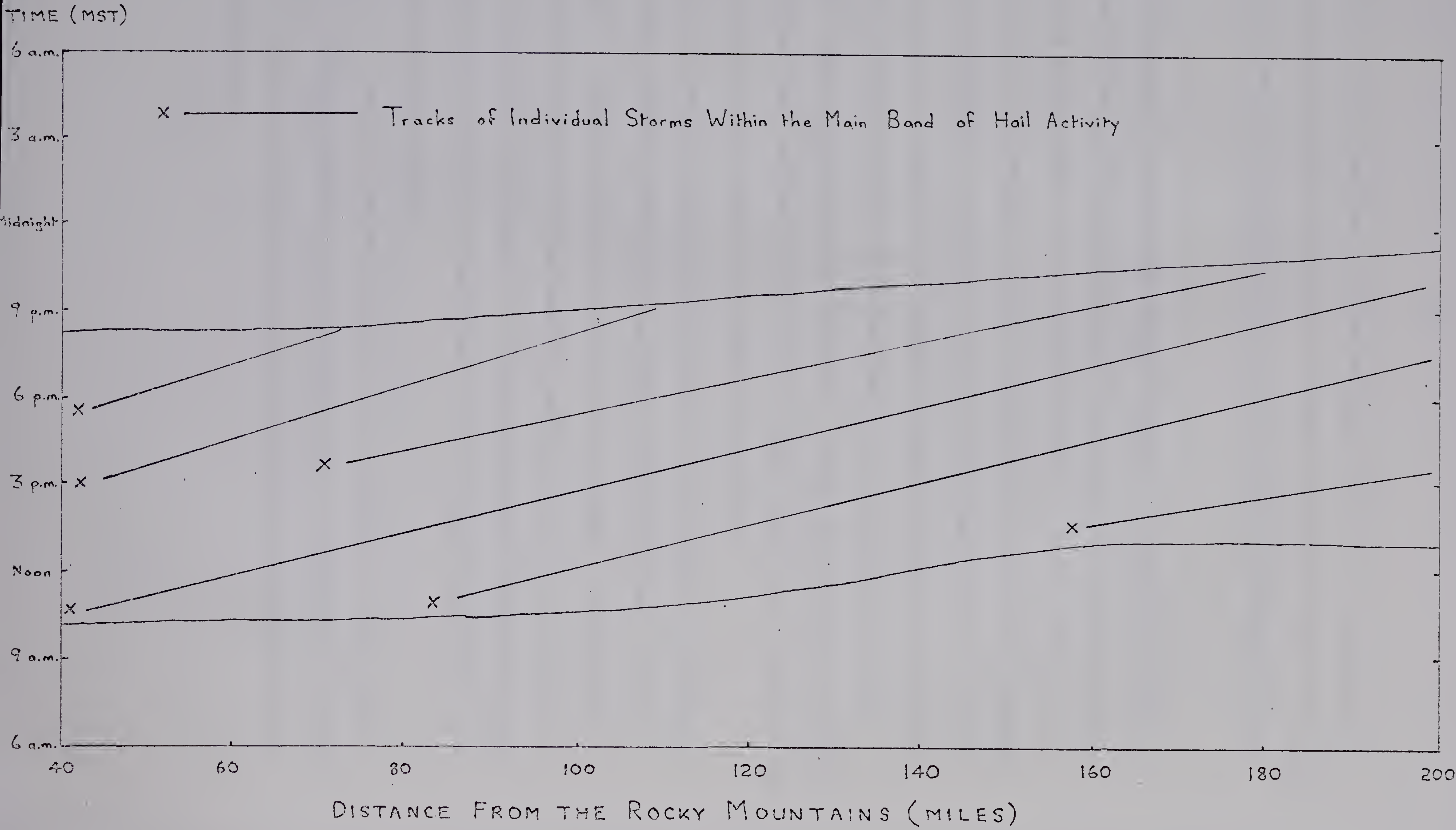
If an idealised picture of the situation were drawn, it would perhaps resemble Figure 21. Allowance has been made for probable errors in reports stating a midnight onset time.

Since the start of the main band of activity is delayed only about two hours over a distance of 160 miles, it cannot be explained simply by hailstorms forming in the foothills area in the west and moving across the whole of the project area, though some of course do this. In general the storms move at a speed of only 20-30 knots. Thus there must be some formation of storms in localities away from the mountains to account for this. In Figure 22, a schematic presentation of this suggestion, "x" marks the origination points of hailstorms, and their tracks are indicated by the solid lines. Only in this fashion can the delay across the project area be adequately explained.

It is interesting to speculate on the areas in which the secondary bands of storm activity seem to originate. Early morning hail appears to start about 115 miles from the mountains, while hailfall in the small hours of the morning seems to occur to a marked degree only in the area more than 160 miles from them. The 9:30 "wave" is present only in the areas closest to the Rockies. Mid-morning hailfall separate from the main band of activity which starts about noon may originate anywhere further than 140 miles from the mountains.

To carry this analysis further, into strips perpendicular to the mountains, would be interesting. Perhaps then the actual localities

FIGURE 22 - SUGGESTED RELATION OF INDIVIDUAL STORMS TO THE OVERALL ONSET TIME PATTERN



responsible for the formation of these secondary "waves" not developing in the foothills zone could be identified. Whether or not the "waves" are simply the result of one or two isolated severe storms could be investigated also.

Summary

Distribution of onset times through the day (reflected in the Mean Onset Time) varies considerably from year to year, depending on the presence or absence in a given year of the secondary "waves" of hail activity. The band of afternoon and evening activity is present in all years and throughout the entire project area. Regional variation of mean onset time may also be regarded as due to the presence or absence of secondary bands of hailstorms.

However, these secondary bands are restricted temporally as well as spatially. Early morning hailfall (7-10 a.m.) during the ten years of project operations has been commonest in the months of June, August and September, and largely confined to the years 1957, 1958, 1960 and 1966.

There is a definite tendency for hailfall to occur later in the day in the more active months, particularly in July, and also for mean onset time to be later as distance from the Rocky Mountains increases. However, the latter trend is offset in the northeastern portion of the area by the more frequent occurrence of hailstorms in the early morning and during the night; on the other hand, it is also accentuated by mid-morning (9:30-10:00 a.m.) hail in the foothills country.

Finally, there is a marked variation in the histograms of onset times for the six different maximum sizes of observed hail. Large hail is confined to a small time-span in late afternoon and early evening; small hail occurs throughout the day.

CHAPTER VII

DURATION OF HAILFALL

The life of a hailstorm may be as long as several hours, but as it is a travelling system the duration of hail at any point is much shorter, usually of the order of a few minutes. Frequently the length of the hailfall varies at different points within the swath produced by one storm. The entire storm in such cases may consist of a series of convective "cells", forming one after another within the body of the main storm. Duration of hailfall at a point on the ground thus depends on the location of that point relative to the development of these thermals. If the storm at one point contains a newly generated cell, and at another a decaying cell, hailfall durations at these two points are likely to be quite different. The length of a hailfall is also very significant to the damage it causes at a particular location.

Duration in minutes has been requested on the cards since the inception of the project. The computer was programmed to put individual answers to this question into nine categories, of class interval three minutes (Table IX), and express the number of reports in each category as a percentage of the total number of reports in which the duration question was answered. The number of cards with duration unknown was also counted by the computer.

TABLE IX - DURATION CATEGORIES PROGRAMMED INTO THE COMPUTER

Class	Duration in minutes	Class	Duration in minutes	Class	Duration in minutes
1	0-3	4	10-12	7	19-21
2	4-6	5	13-15	8	22-24
3	7-9	6	16-18	9	25 and up

The bias of reporters towards multiples of five minutes, already remarked upon, was again evident, so that it was decided to combine Classes 1 & 2, 3 & 4, 5 & 6 and 7 & 8 to eliminate this bias. Tables presented in this thesis for duration data thus consist of five categories; the first four each contain only one multiple of five minutes, and have a class interval of six minutes, while the fifth is the same as Duration Class 9 in the original computer output. Mean values of duration were also worked out by the computer.

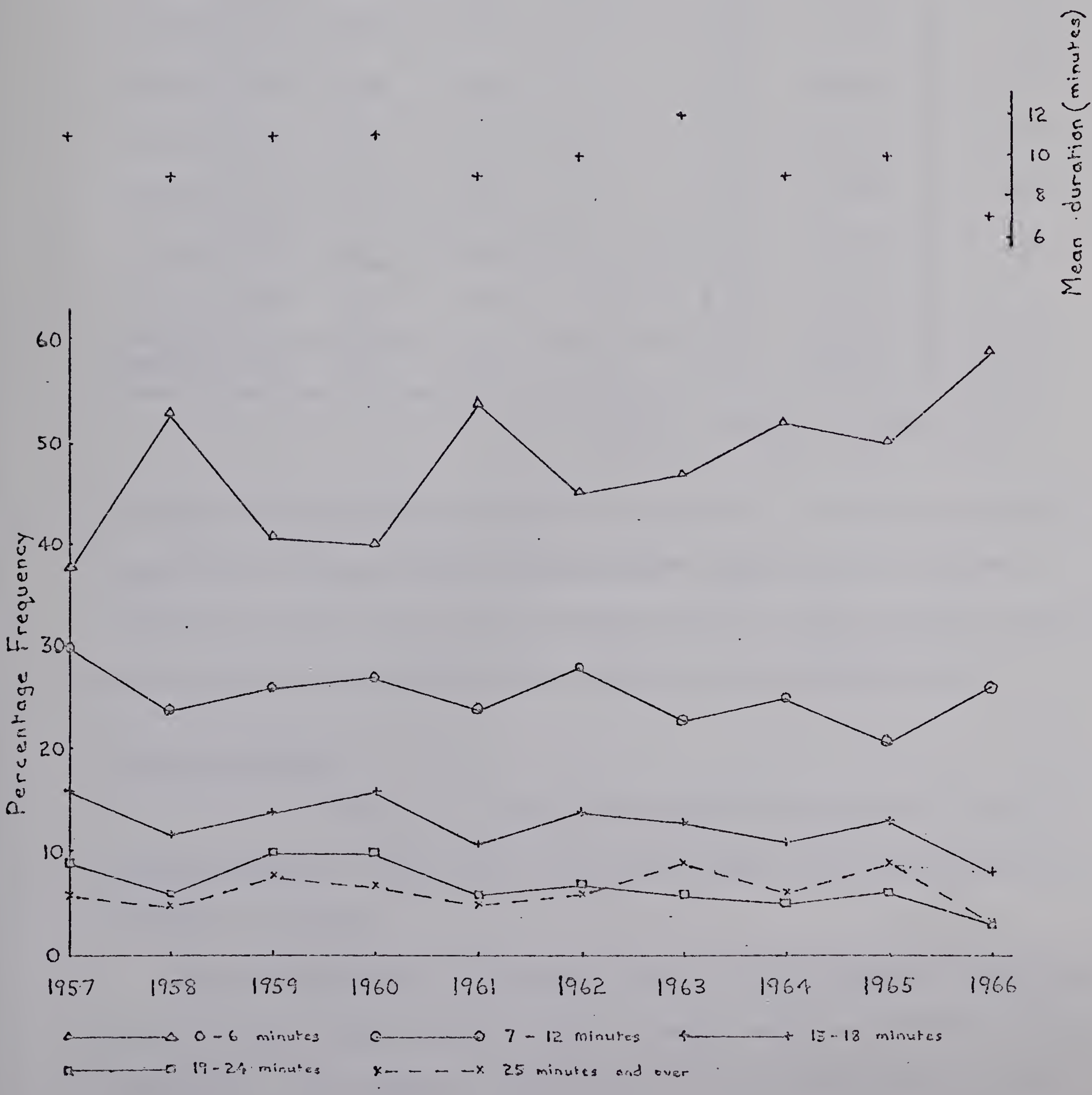
Year-to-Year Variation

Table X gives the percentage frequency in each year of the five duration categories formed by combination of the nine classes in the original computer output, thus eliminating the effect of the observing bias described in Chapter III. The upper portion of Figure 23 shows the variation of the mean duration for each year put out by the computer. There is a tendency for the mean length of hailfall to rise in the most severe years (for example 1963 and 1957) and drop during the lighter ones such as 1958 and 1961. Surprisingly, the value for 1966 is lowest of all, at seven minutes, but apart from this there is little of note. The overall mean duration for the entire period is ten minutes.

The percentage frequency of the different duration categories (Figure 23) is more revealing, and a slight tendency for duration to decrease through the ten-year period is evident, particularly in a marked increase of the occurrence of the 0-6 minute group. A decrease in the frequency of 7-24 minute durations can be discerned, but is offset somewhat by an increase in the latter years of the 25 minutes and more class. Again, 1966 stands out as a year when hailfalls were quite definitely shorter than in all other years, no matter how light these may have been.

To sum up, there appears to be a slight trend for hailfall duration to

FIGURE 23 - DURATION FREQUENCY DISTRIBUTIONS AND MEAN HAILFALL DURATION BY YEAR



Source: Computer analysis, 1967

TABLE X - PERCENTAGE FREQUENCY BY YEAR OF DURATION CLASSES

Year	Duration in minutes					Total cards scanned	No. of unknowns
	0-6	7-12	13-18	19-24	25+		
1957	38	30	16	9	6	3479	100
1958	53	24	12	6	5	973	15
1959	41	26	14	10	8	3477	80
1960	40	27	16	10	7	2945	105
1961	54	24	11	6	5	521	14
1962	45	28	14	7	6	4248	213
1963	47	23	13	6	9	3998	306
1964	52	25	11	5	6	3783	346
1965	50	21	13	6	9	3781	388
1966	59	26	8	3	3	3179	240
Overall	47	26	13	7	7	30384	1807

Source: Computer analysis, 1967

decrease through the period of project operations. To take the extreme cases, 62 per cent of 1957 hailfalls lasted longer than six minutes, compared with only 41 per cent of those of 1966. Apart from this, duration would seem to be a function of the severity of an individual year.

Seasonal Variation

Table XI contains the relative frequencies of the five duration classes in each month of the hail season, and the mean duration of hailfall in minutes.

June and September, with means of nine and eight minutes respectively, are the months which bring the overall average length of hailfall down to ten minutes. The frequency distributions for July and August are very

TABLE XI - DURATION CLASSES BY MONTH

Duration (minutes)	Percentage Frequency of Reports				
	May	June	July	Aug.	Sept.
0-6	41	49	47	44	57
7-12	30	26	25	24	25
13-18	14	13	14	14	11
19-24	7	6	7	8	3
25 and up	8	5	7	8	4
Mean Dur. (minutes)	11	9	11	11	8
Reports of unknown Dur.	17	383	854	538	15
Total cards scanned	482	10131	12755	6509	506

Source: Computer analysis, 1967

similar to each other, and June despite a mean value of nine minutes, shows only a slightly greater leaning towards the classes of shorter duration. As might be anticipated, September has a lower proportion of reports, 18 per cent, than the summer months (June 24, July 28 and August 30 per cent) stating hailfall longer than twelve minutes. But May shows a very different distribution, 29 per cent of the known durations being longer than twelve minutes, while only 41 per cent are less than seven minutes (cf. August 44, July 47, June 49 and September 57 per cent). It might perhaps be expected that storms in May and September, which are relatively infrequent and less severe than those of high summer, would be of short duration. September hailfalls are, but those of May are not.

It is likely that, since the storms in May for which reports have been received are close to the end of the month, they will tend towards June hailstorms in terms of behaviour. There would thus be a reasonable

case for them to last longer than September storms, reports for which are spread more evenly through the month.[1] However, this does not explain the May mean duration of eleven minutes, the average value for June being only nine minutes. In terms of the frequency distribution through the five categories also, hailfall durations in May seem to be more akin to those of August. But August appears from its distribution to be the month in which hailfall generally lasts longest. Perhaps the most feasible suggestion is that the 465 known durations on which the May analysis is based represent an inadequate sample. They are mostly from a few severe storms near the end of the month, particularly in 1965 and 1966.

Spatial Variation

A programme was included in the computer analysis to extract the percentage frequencies of occurrence of the nine duration categories for each of the 216 regional units. As described previously, the area analysed was reduced and some of the units combined to produce a total of 122 data points for mapping purposes. Even so, in three of the regions thus formed the number of reports specifying a duration fell below the hundred. Again the duration classes were combined into five. Appendix G consists of a series of three maps showing the spatial variation of percentages of reports falling into the 0-6, 13-18, and 25 minutes and over duration categories.

Figure 24 is a map of mean duration of hailfall over Central Alberta, drawn up in the same way as the map of mean onset time discussed in the previous chapter. In a way it is simply a summary of Appendix G. Several interesting features are present.

There are three regions which stand out from the areas round about

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[1] See Appendix B.

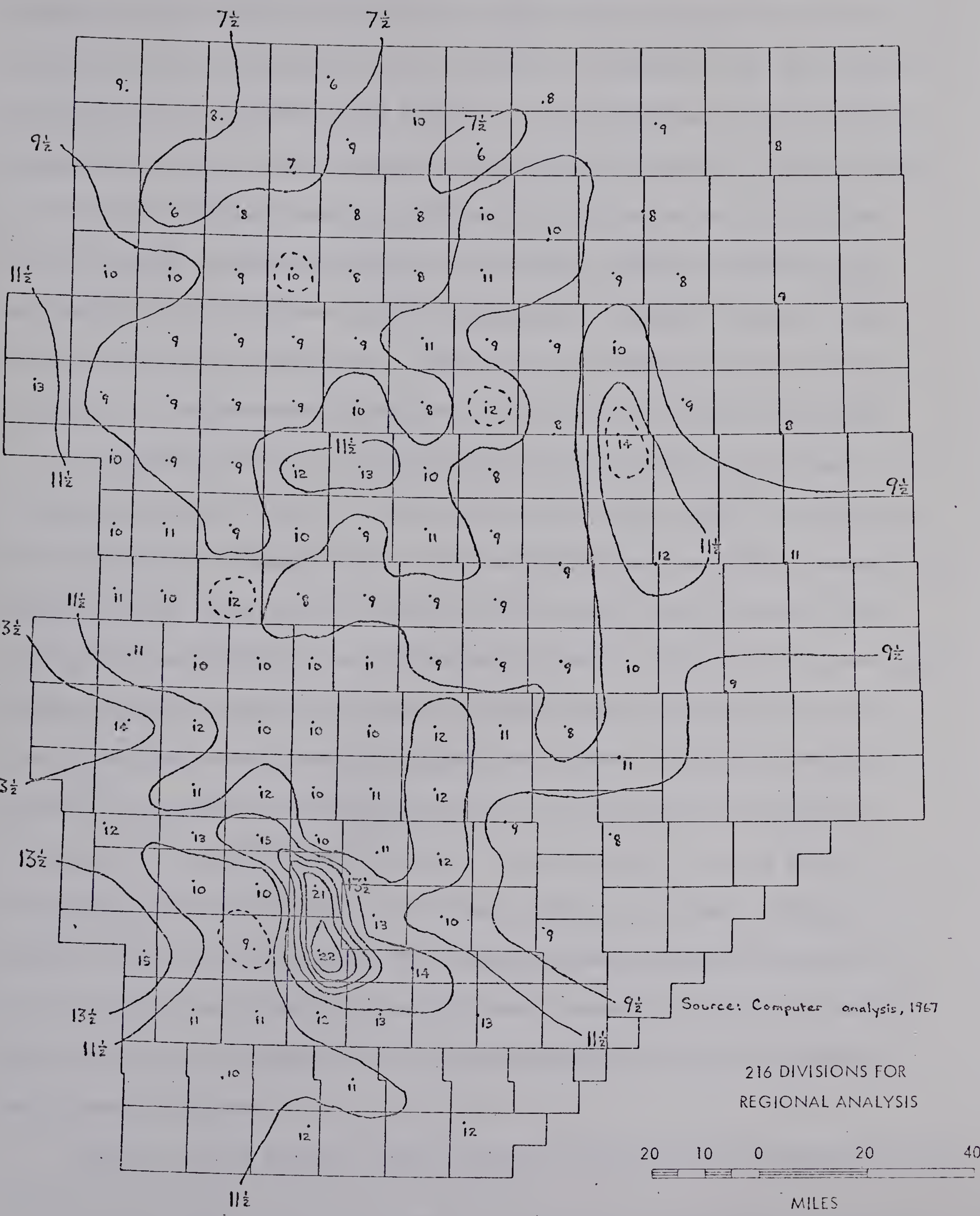

FIGURE 24 - MEAN HAILFALL DURATION IN MINUTES IN CENTRAL ALBERTA, 1957-66

by virtue of their experiencing, on the average, longer hailfall. The most significant lies just to the east of Calgary and is centred on the only two regional units (a contiguous area of almost 250 square miles) which have a mean duration of reported hail longer than twenty minutes. The Stettler region has a belt of high average duration (12-14 minutes). Finally, there is a tract of country running approximately northeastwards from an area west of Bowden through the vicinity of Red Deer (average duration 12 minutes) almost to Camrose in which duration of hailfall tends to exceed that of the areas adjoining it. This tract may perhaps be traced even further in a southwesterly direction to the region of Sundre and Bergen.

To suggest a reason for the existence of these belts is not easy. It seems possible that storms of some severity may have tended to move along the 130-mile track from Sundre to Camrose in the past ten years, consequently giving rise to longer falls of hail. It is thought that the major river valleys of the foothills country may be a prominent "source" of convectional storms; and the tract of land under review follows the course of the Red Deer River for a considerable distance from Sundre. It is noticeable, speaking of major river valleys, that the two other zones of high hail duration are on the "downwind" side of two of these, i.e. the Bow at Calgary, and the section of the Red Deer south of its great bend near Nevis. Powell has referred to the relation between physiography and hail in the region, and it may be that increased convectional activity tends to have a rejuvenating effect when a declining hailstorm passes over such a major relief feature.[2]

Turning to more general trends visible on the map, and disregarding the

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[2] Powell, G.L., The Relationship of Physiography to Hail in Alberta, unpublished M.Sc. thesis, University of Alberta, Edmonton, 1961.

the features mentioned above, it is evident that hailfall in the foothills zone, particularly in the southwest, has the longest durations. Mean durations shorter than ten minutes, which is the overall average length of hailfall, are not found in the southern and western portions of the area.[3] The southern half of the area has for the most part mean durations longer than ten minutes, and the only segments with mean hailfalls lasting six and seven minutes are in the northwest. Thus there also appears to be a slight tendency for the average duration of hail to decrease from south to north. This may simply be a result of increasing latitude; the slight temperature gradient across Central Alberta suggests that conditions necessary for severe and long hailfalls are less likely to occur the further north the location.

In summarising this section, it is useful to turn to the maps of Appendix G and note the following points;

(i) the only significant area with less than 40 per cent of its hailfalls shorter than seven minutes is found in the southwest (Map #1),

(ii) only northwards from the latitude of Hobbema does a major portion of the area have more than 60 per cent of its hailfalls shorter than seven minutes (Map #1),

(iii) more than 15 per cent of the hailfalls recorded by three of the regional units in the vicinity of Calgary lasted twenty-five minutes or longer (Map #3). The only other unit attaining a similar value is around Rocky Mountain House, while values in the northern and eastern parts of the project area average only 5-6 per cent.

<u>Variation With Distance From the Mountains</u>

As before , the duration classes

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[3] This point is expanded in the next section of this chapter.

put out by the computer for each of the forty-seven categories of distance from the Rockies were combined to eliminate observing bias.[4] For each category, a mean duration was also derived by the computer, and the upper portion of Figure 25 shows the variation of this with increasing distance from the mountains. There seems to be a tendency for the longest durations to be experienced closest to the Rockies. This is convincingly demonstrated by the variations in percentage frequency presented graphically in the lower portion of Figure 25.

A definite tendency for the percentage frequency of reports stating a duration of 0-6 minutes to increase with distance from the mountains is evident. All the other four classes of duration show a slow decline in this direction. To reduce the situation to its utmost simplicity, the probability of a hailfall lasting longer than six minutes is generally more than 60 per cent at less than 75 miles from the main divide and decreases with distance to around 40-45 per cent further than 200 miles.

One inference that can be drawn from these duration data is that the travelling convectional storms producing the majority of Central Alberta hail tends to move only slowly during the early stages in the foothills and accelerate away on developing to maturity. This assumes that during the storm movement the hail-producing cell or cells remain the same size, or are at least fairly constant in magnitude. Many storms die away after moving into the prairie region, so that hailfall in this area is often short-lived. Indeed the hail falling towards the end of a storm's life may be limited to only a few stones.

<u>Summary</u>

There seems to be a slight tendency for duration of hail at a point

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[4] See Appendix H for details.

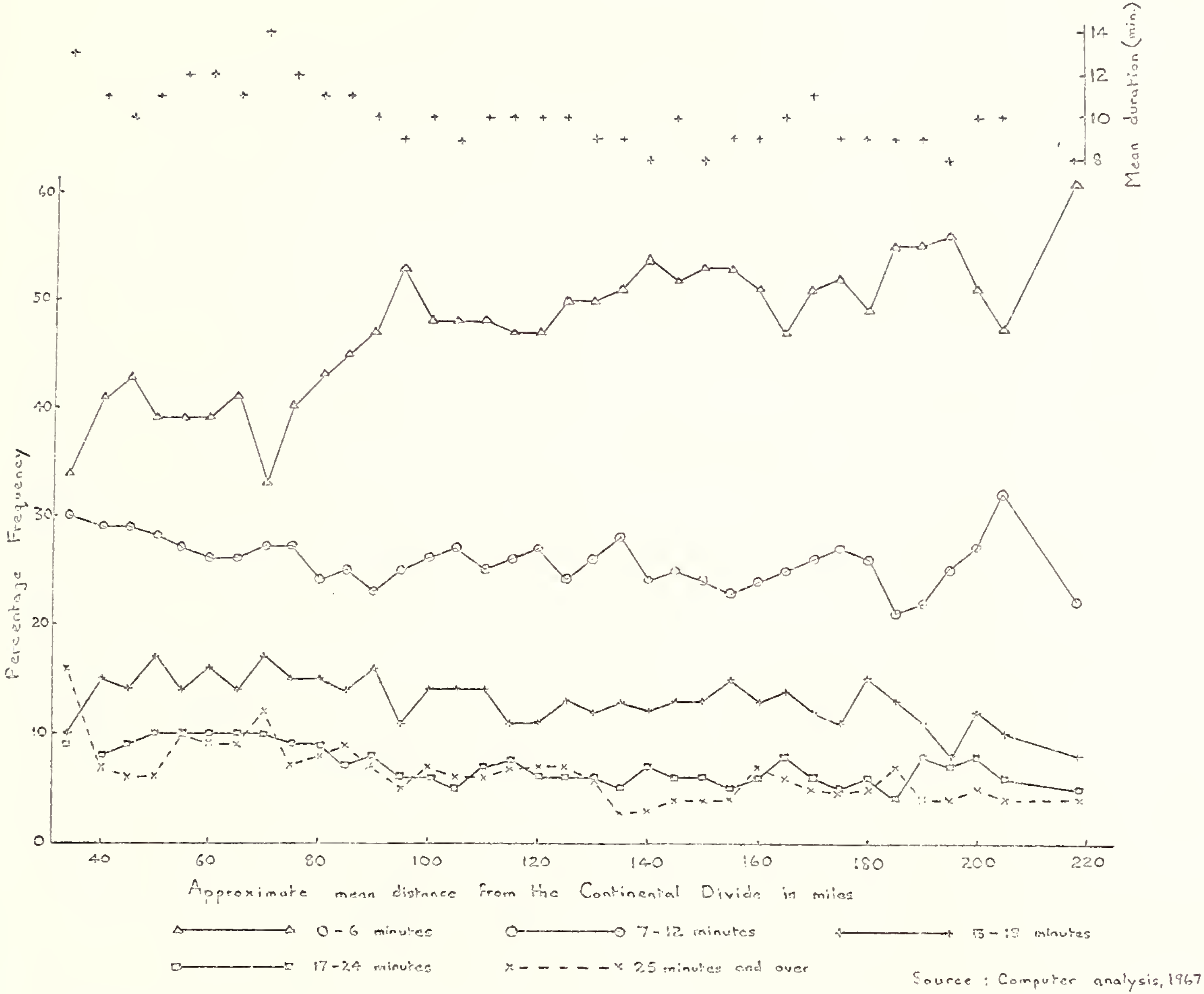

FIGURE 25 - DURATION FREQUENCY DISTRIBUTIONS AND MEAN HAILFALL DURATION BY DISTANCE FROM THE ROCKY MOUNTAINS

CHAPTER VIII

MAXIMUM SIZE OF OBSERVED HAIL

This analysis, like that of Chapter IV, is based on the various hail logs and monthly and seasonal summaries which are available. It includes all ten years of data. Again, however, the relevant information for 1962 had to be extracted from the punched cards by the computer.

The data are simply based on the answer to a single question on the report card, namely: "What was the size of the largest hail?" In answer the observer checks the box appropriate to the largest stones he saw during the hailfall. Rather than refer to actual dimensions, it was decided to classify the size into general categories associated with objects familiar to everyone. Table XII lists these.

TABLE XII - HAIL SIZES

Object	Size Class Code	Diameter (mm.)	Av. Radius (mm.)
Shot	1	1-4	1
Pea	2	4-12	4
Grape	3	12-20	8
Walnut	4	20-32	12
Golfball	5	32-50	20
Larger than golfball	6	50+	30
Unknown Size	0		

It has been suggested by Williams and Douglas that "in general, reports of the smaller sizes of hail are obtained by survey rather than by

the regular mailed reports".[1] The present writer, however, has studied both the survey and unsolicited reports received up to 1966 and investigated the relation between large hail (walnut and bigger) and all hail of known size; there is no evidence in this analysis of any size-bias in the survey technique. For both survey and non-survey reports the ratio of large hail to all hail reported has a value of 1:4.2, and there is no significant difference between the two values of the ratio in a spatial sense. Therefore it is reasonable to use all Alberta Hail Studies reports, regardless of how each was obtained, in this analysis of maximum observed hail size.

Year-to-Year Variation

Figures 26a and 26b show frequency distributions of maximum hail size by year. The years show considerable fluctuations; generally it seems that the more active the year, the higher is the proportion of large hail and the lower the proportion in the smaller categories. This point is brought out even more effectively in Figure 27. Here the six size classes have been reduced to three - small hail (shot and pea size), grape size, and large hail (walnut and bigger). Appendix J gives the tabulations from which Figures 26 and 27 are drawn.

It is apparent that large hail, i.e. upwards of about an inch in diameter, is very common in Central Alberta. In 1957, 1960 and 1964 more than one report in five specified that some large hail was observed. Only in 1958, during which year activity was light, has this ratio dropped below one in ten.

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[1] Williams, G.N., and Douglas, R.H., Continuity of Hail Production in Alberta Storms, Scientific Report MW-36, Stormy Weather Research Group, McGill University, Montreal, August 1963, p. 47.

FIGURE 26a

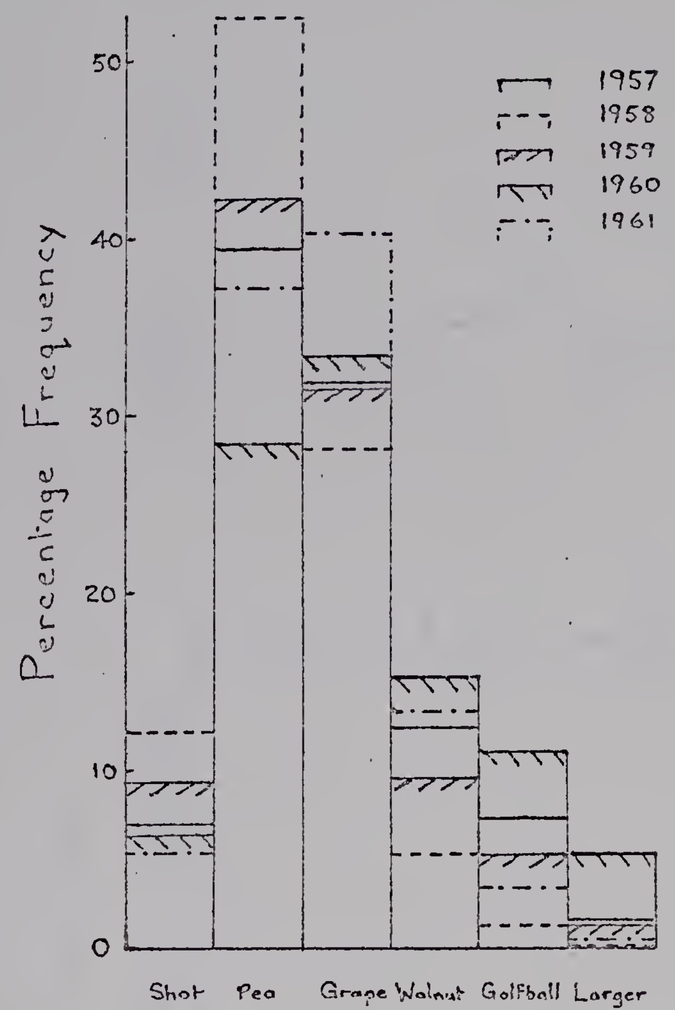
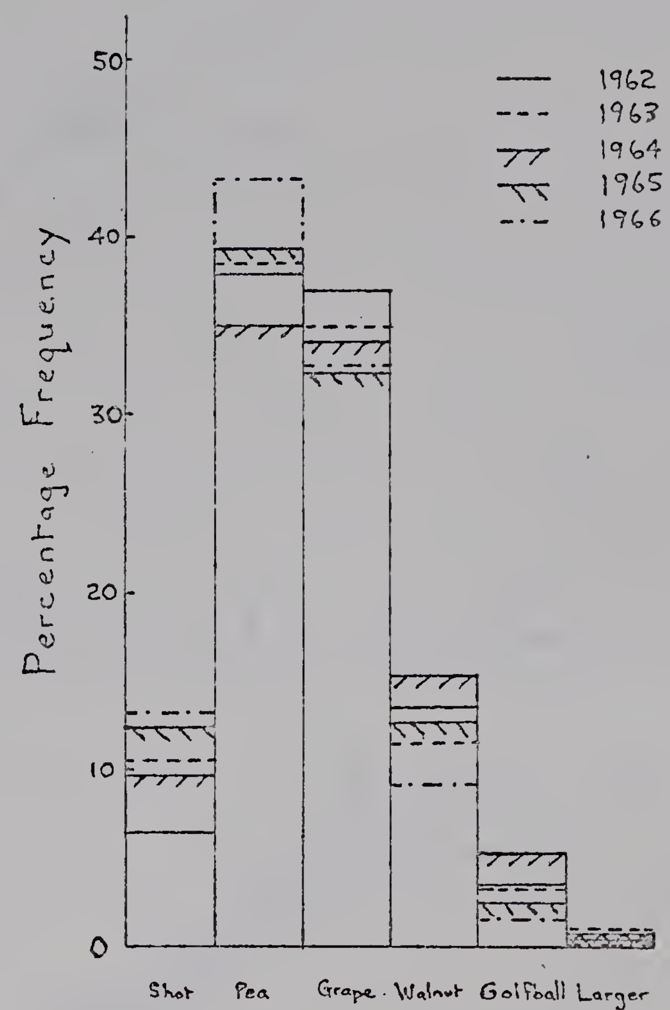


FIGURE 26b



Source: Alberta Hail Studies records

FIGURE 26 - YEARLY HISTOGRAMS OF MAXIMUM HAIL SIZE

(a) 1957-61 (b) 1962-66

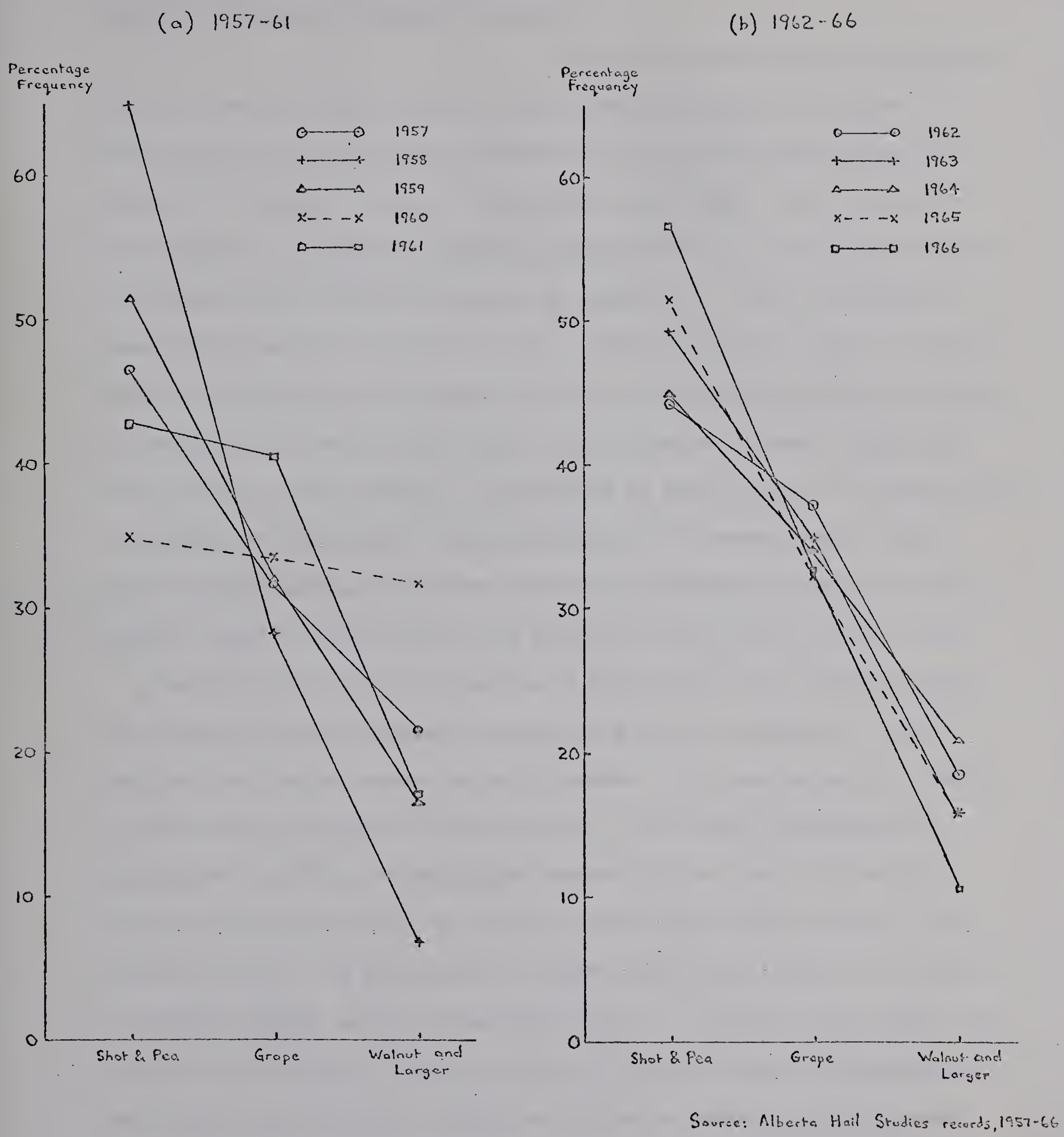


FIGURE 27 - HISTOGRAMS OF SMALL, MEDIUM AND LARGE HAIL REPORTED BY YEAR

Seasonal Variation of Maximum Hail Size

Since June and July are the heaviest months in terms of hail days and reports respectively, it is rather surprising that the percentage frequency of large hail (walnut-size and greater) is highest in August (Table XIII; Figure 28b). For in year-by-year analysis, it appeared that the higher the total of unsolicited reports, the higher is the relative incidence of large hail. Hence the seasonal peak might be expected to fall in July. Its occurrence in August, however, tends to conform with the seasonal variation of hailfall duration discussed in the previous chapter, where August again appears to have a slight edge over the other summer months. The presence of large hail and a long duration of hailfall are behavioural characteristics of the severe storm; hence, August storms seem to be the most severe hail producers in Central Alberta. However, they are less frequent and extensive than those of June or July.

Table XIII (visually represented in Figure 28a) is an overall summary of the month-by-month maximum hail size data given in Appendix J, which is compiled from various summaries and log-books. The same tendency as exists in year-to-year variation is again evident. Small hail predominates in months when the total of unsolicited reports is low, and its proportion decreases as the intensity of activity rises (Figure 28b) so that it has a minimum in July. The percentage of reports specifying large hail, however, is slightly higher, as has already been noted, in August (23 per cent) than in July (22 per cent). This is in spite of the fact that the percentage of small hail is also slightly higher, and forms an exception to the general trend of large hail percentage frequency in any period to be related to the number of unsolicited reports received.

Source: Alberta Hail Studies records, 1957-66

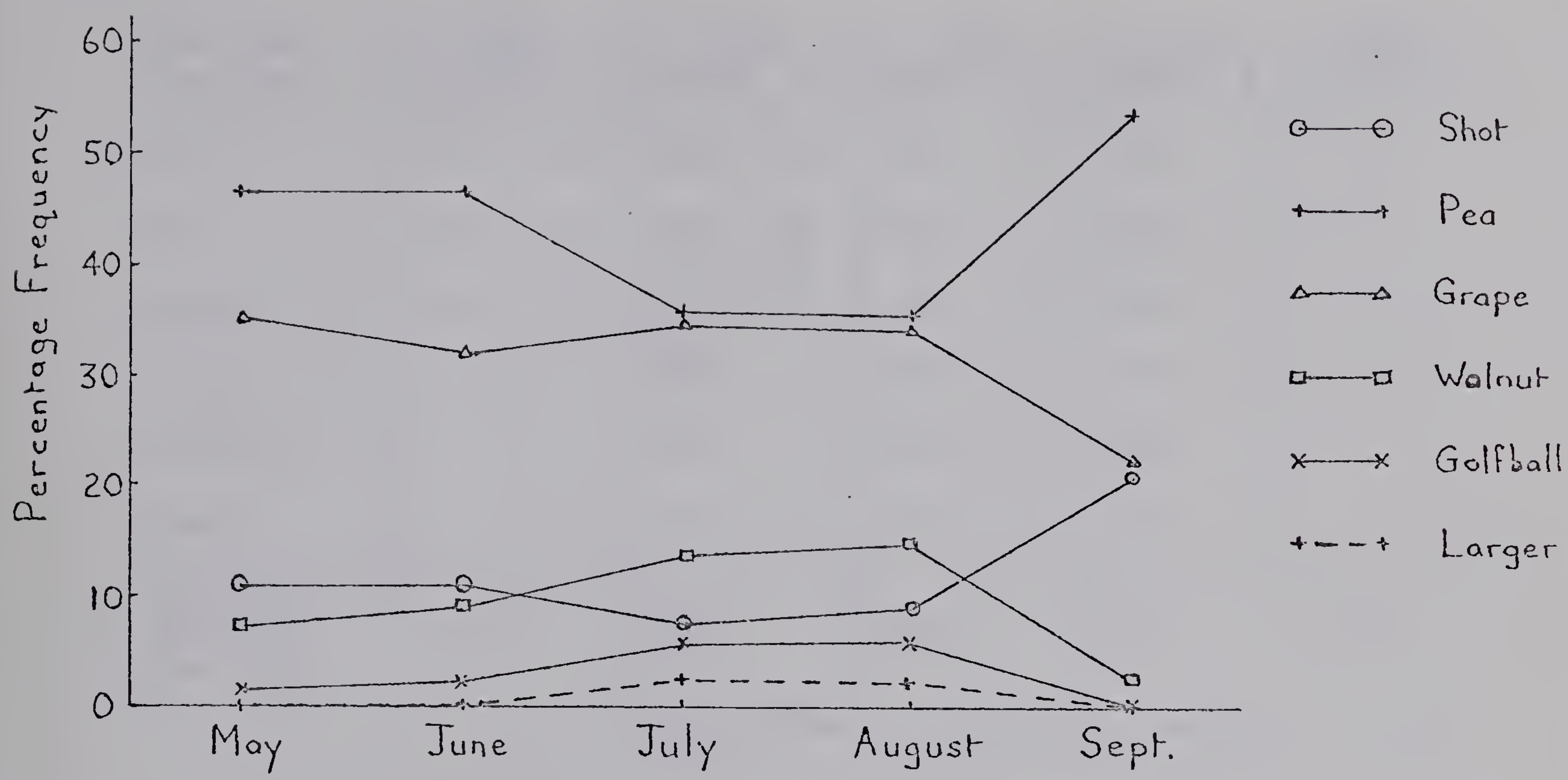
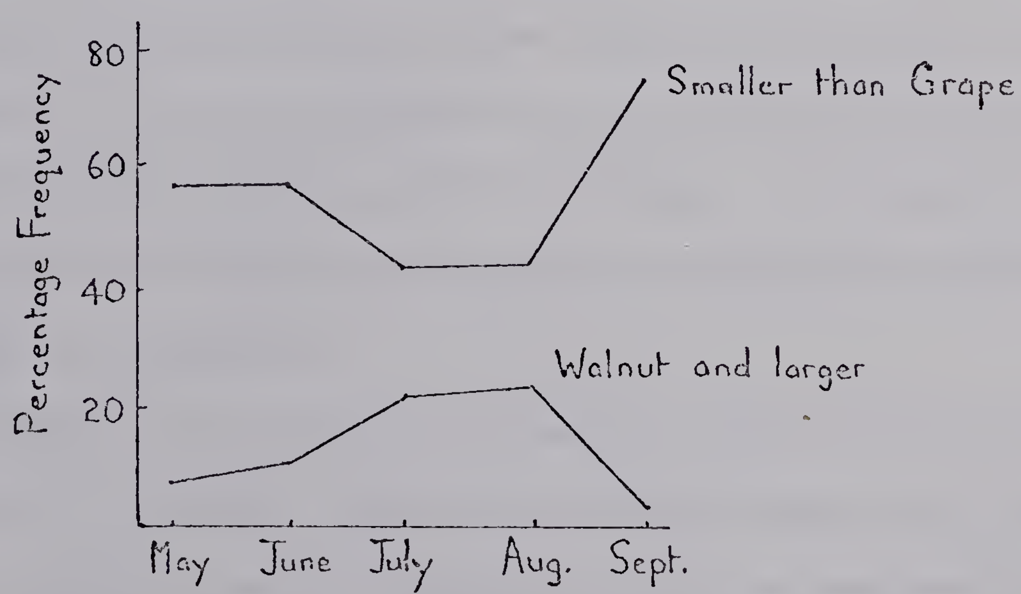


FIGURE 28a - PERCENTAGES BY MONTH OF SIX DIFFERENT MAXIMUM HAIL SIZES



Source: Alberta Hail Studies records, 1957-66

FIGURE 28b - SEASONAL SMALL AND LARGE HAIL

TABLE XIII - OVERALL SEASONAL VARIATION OF MAXIMUM HAIL SIZES

Max. Size Observed	May		June		July		Aug.		Sept.	
	Cards	%	Cards	%	Cards	%	Cards	%	Cards	%
Shot	51	11	1112	11	941	8	561	9	98	21
Pea	217	46	4494	46	4292	35	2119	34	245	54
Grape	166	35	3186	32	4391	35	2069	34	103	22
Walnut	33	7	883	9	1738	14	928	15	13	3
Golfball	3	1	237	2	788	6	364	6	1	0
Larger	0	0	15	0	259	2	101	2	0	0
Total with specified Max. Size	470		9927		12409		6142		460	

Source: Alberta Hail Studies records, 1957-66

Spatial Variation

A section in the computer programming provided for extraction of the variation of large hail incidence over the area. As it was not certain prior to the performance of the analysis whether or not the survey technique involved any unreasonable bias towards the reporting of one size range or another, the output was made such that unsolicited reports could be separated from the overall totals if necessary. In actual fact no such problem arises, and consequently all reports scanned by the computer in this investigation are considered.

An examination of the regional variation of the ratio of reports with some large hail to the total reports specifying a maximum hail size (henceforth referred to as the "Large Size Ratio" and expressed as a percentage) was then performed for the areal units. Figure 29 gives the results. There are several small areas in which the ratio exceeds 30 per cent, and some quite large areas where its value is 20 per cent or more. However, no general trends seem to be visible through the whole region;

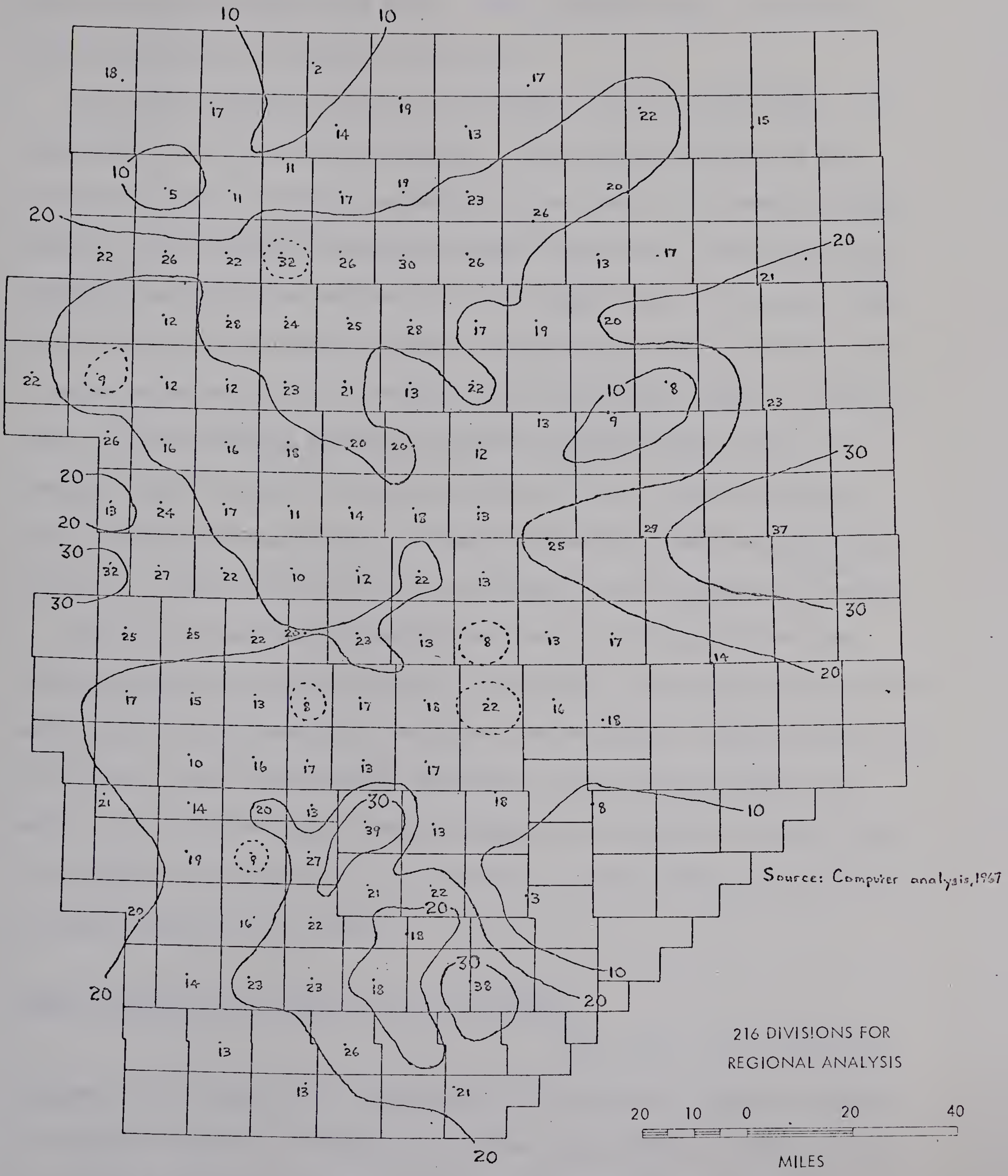


FIGURE 29 - PERCENTAGE OF REPORTS WITH LARGE HAIL IN CENTRAL ALBERTA, 1957-66

areas where the ratio is above average are well-scattered, as are those with below-average Large Size Ratio. There are also sharp transitions in many localities from a high to a low ratio.

Four major regions stand out as having a high Large Size Ratio. The most marked is in the extreme southeast of the project area, with its maximum of 39 per cent being registered a few miles to the east of Calgary. Another is the Sullivan Lake-Castor region in the east, while much of the foothills country in the extreme west has a Large Size Ratio greater than 20 per cent; the James River Bridge area has 32 per cent. From this belt a tongue protrudes into the Torrington-Knee Hill Valley region. Finally a tract of land extending east and northeast from the northern end of the foothills belt has values in excess of 20 per cent. From the country south of Buck Lake in the west, it takes in the Gull Lake area, with Red Deer to the south, and tapers off over Ponoka to the northeast of Camrose.

There are some similarities between the map of Figure 29 and that showing duration of hailfall; this is reasonable, since both properties are indicators of storm severity. But there are exceptions. The Stettler area, for instance, with above-average durations, has a very low Large Size Ratio. It is interesting to compare Figure 29 with some of the other maps of hail behaviour properties, but more will be said on this subject in the closing chapters of this thesis.

Large Size Ratio and Distance From the Rockies

For each of the forty-seven categories of distance from the mountains, the computer analysis supplied the number of reports of large hail and the total number of reports where the maximum size was specified. The Large Size Ratio could then be calculated, and Figure 30 shows its variation with increasing distance from the Rocky Mountains.

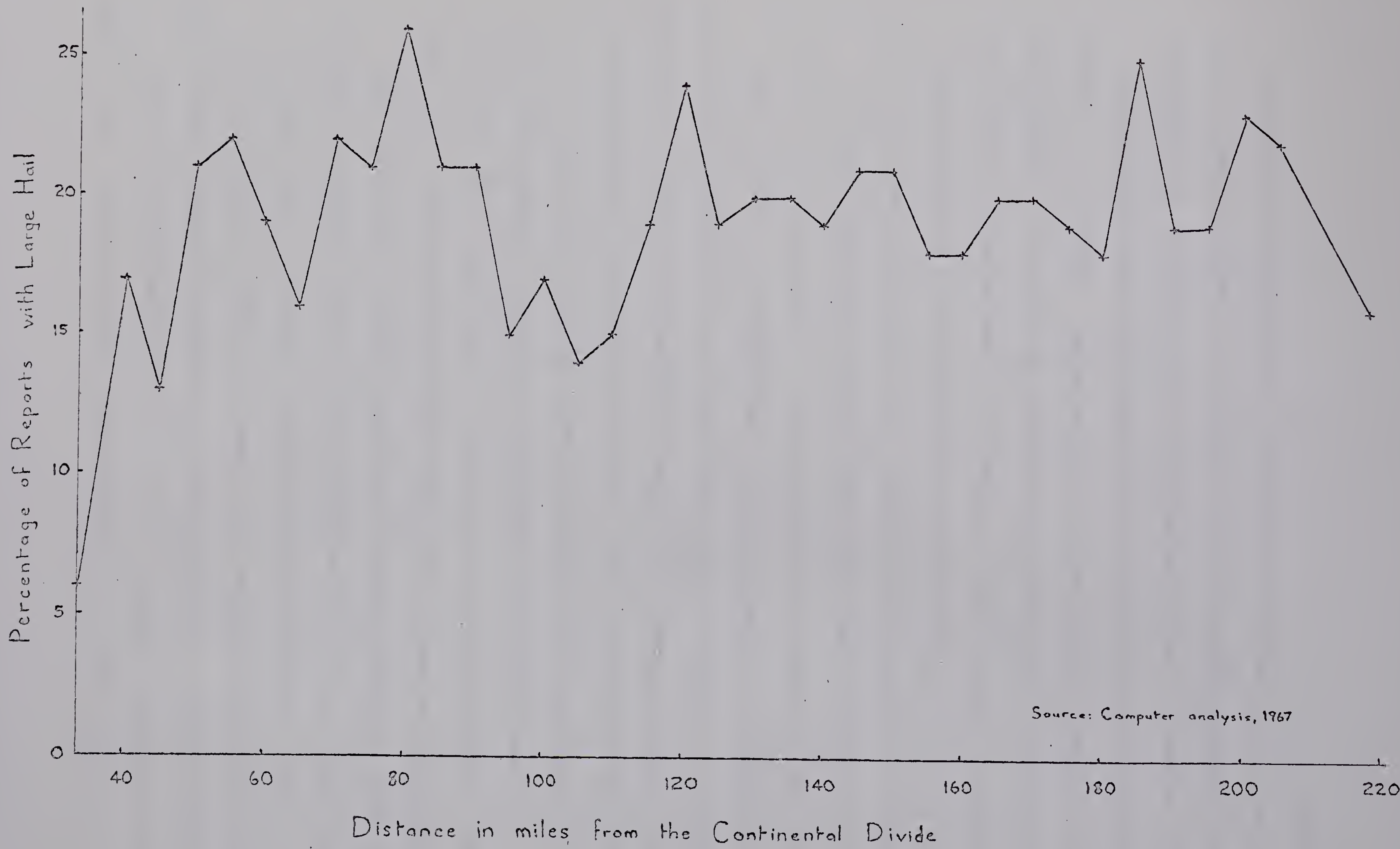


FIGURE 30 - LARGE HAIL RATIO AND DISTANCE FROM THE ROCKIES

The point made in the previous section, that no general trends in this ratio are present over the area as a whole, is supported by this more specific analysis. Certainly there is no significant overall change in the ratio as distance increases. The peaks of the graph in Figure 30 seem to tie in well with the distribution evident in Figure 29. The trough on the graph around 90 to 115 miles distant from the Rocky Mountains is visible on the map as a diagonal "slice" of land some twenty to forty miles wide, running from northwest to southeast right through the middle of the project area, and having in the main an average or below-average Large Hail Ratio.

It seems possible that this "gap" in large hail incidence may in part be a consequence of the propagation factor mentioned in the discussion of Hail Onset Time (Chapter VI). It will be recalled that the explanation of onset time distributions necessitated the generation of storms in localities besides the foothills. It is likely that there are preferred locations for the triggering of convective activity, and perhaps the zone 120 to 130 miles from the Rockies has several of these. Towards the end of a storm's life, the maximum size of hail being produced is declining; thus the formation of storms in the foothills, some of which fade away in the region 90 to 120 miles out from the mountains, combined with a renewal of storm generation a little further on (supported to some extent by the onset time distribution), could explain the occurrence of this belt of low Large Size Ratio oriented roughly parallel to the mountains. Figure 31 is a schematic presentation of this argument, which assumes that storms generally have a major component of motion perpendicular to the mountains. Its similarity to the diagram (Figure 22) used in Chapter VI to suggest a reason for the observed onset times at given distances from the Rockies is immediately apparent.

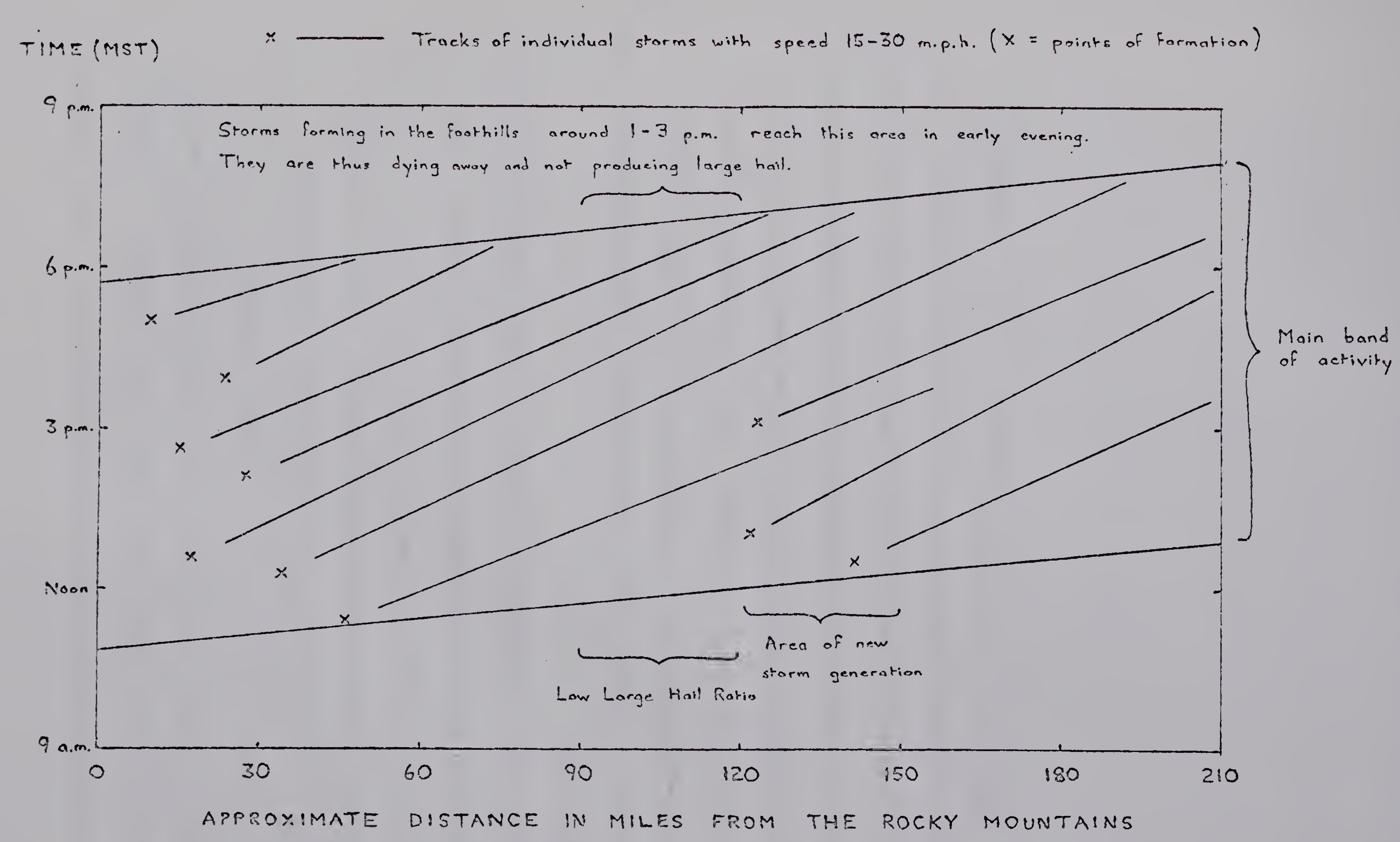


FIGURE 31 – THE AREA OF LOW LARGE HAIL RATIO 90-120 MILES FROM THE CONTINENTAL DIVIDE

Summary

Surveys are not biased towards the reporting of any particular size of hail, and therefore all reports were used in this analysis. Taken as a whole, more than one report in five in Central Alberta mentions some hail of walnut size or larger, i.e. one inch or more in diameter.

Maximum hail size frequency distributions show a considerable variation from year to year and from month to month. Broadly speaking, there seems to be some relation between the form of the size histogram and the intensity of hail activity. However, in the period 1957-66, August has been the month with the highest percentage of large hail reported over the whole project area.

Spatial analysis reveals areas of above-average Large Hail Ratio, some of which appear to coincide with the regions of above-average hailfall duration described in the previous chapter. Also a diagonal stretch of country from the Leslieville-Carlos area in the northwest through to the Drumheller-Rockyford region in the southeast (with the exception of some of the land around Torrington, Knee Hill Valley and Carbon) experiences in the main only average or below-average values for the Large Size Ratio. But no general overall trends across the entire project area can be identified.

CHAPTER IX

ALBERTA DATA COMPARED WITH OTHER AREAS

Detailed information on hailfall similar to that collected by Alberta Hail Studies is sparse. This chapter is an attempt to discuss what is available and compare the properties of Alberta hail with those observed in other parts of the world.

Hail Days

The Central Alberta network is large and the observer spacing is quite dense. Since the reporting of hail is a function of area and degree of coverage, the hail day figures are not strictly comparable with those of other institutions recording hail on an areal basis. However, a literature search has produced some data of this type, and they are summarised in Table XIV.

Co-operative volunteer reporting has yielded the data for the Denver, Western Kenya and Transvaal networks.[1,2,3,4] Crop-hail insurance records were analysed by Frisby and Blakmer for South Dakota and Illinois respectively.[5,6] As these data are based on hail damage claims, they are liable

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[1] Beckwith, W.B., "Characteristics of Denver Hailstorms", Bull. Amer. Met. Soc., Vol. 38, No. 1, January 1957, pp. 20-30.

[2] Idem, "Analysis of Hailstorms in the Denver Network, 1949-58", in Weickmann, H. (ed.), Physics of Precipitation, Baltimore, Waverly Press, 1960, pp. 348-353.

[3] Sansom, H.W., "The Occurrence and Distribution of Hail in Africa", Met. Mag., Vol. 95, No. 1128, July 1966, pp. 212-218.

[4] Carte, A.E., "Hailstorms in South Africa", South African Weather Newsletter, No. 193, April 1965, pp. 58-61.

[5] Frisby, E.M., "Hailstorms of the Upper Great Plains of the United States", J.Appl. Meteor., Vol. 2, No. 4, December 1963, pp. 759-766.

[6] Blackmer, R.H., Jr., in Stout, G.E. et al., The Hail Hazard in Illinois, preliminary report for the Crop-Hail Insurance Actuarial Association, Chicago, 1959.

TABLE XIV - HAIL DAYS ON AN AREAL BASIS

Region	Denver	W. Kenya	Transvaal	S. Dakota	Illinois	C. Alberta
Period	1949-58	1960-64	1962-65	1951-60	1948-57	1957-66
Area in sq. mls.	250	20,000	1,000	80,000	50,000	30,000
January		5	14.0			
February		6	11.0			
March		13	5.0			
April	1.0	9	4.0			
May	5.6	9	1.0	1.7	2.2	7.6*
June	6.4	13	2.0	14.6	8.3	20.3
July	4.4	10	1.0	17.5	7.2	20.3
August	3.3	15	1.0	15.9	5.6	15.7
September	1.6	15	-	1.8	3.0	4.9
October	0.7	10	14.0		0.6	
November		5	12.7			
December		4	13.0			
Yearly Total	22.4*	114	78.7	51.5	26.9	68.8

* The record for May in Central Alberta is not complete, and the figure quoted is likely to be an under-estimate. Monthly averages for the Denver network are based on the seven years 1949-55, but the yearly average is from ten years of records, 1949-58.

to be conservative indicators of hail frequency, and are also subject to certain disadvantages not present in volunteer network reporting. Blackmer states:

> "The data...are partially inadequate because of the small amounts of crop-hail insurance written in Illinois during the period and also because only parts of the records are in a form amenable

> for this study....In situations where several parties have part interest in one crop...it was possible to have several paid losses with only one isolated hail occurrence....Since there was the possibility that a farmer might not know on which of several days hail occurred, if he examined his crops intermittently, it was decided that only days with more than twenty losses would be considered hail days. An exception to this criteria (sic.) was in 1948-50 when ten losses was arbitrarily chosen as the lower limit and in 1951 when fifteen was chosen...to compensate for incomplete data."[7]

Besides the detailed data presented in the table and based on several years of records, the writer has also found references to hail day totals in three other areas. Hitschfeld and Douglas received about five hundred reports from an experimental volunteer network, some thirty thousand square miles in extent, in the Montreal area in the summer of 1956.[8] Hail was reported on 44 of 145 days between May 19 and October 10. The Swiss Hail Insurance Company, with seventy-five years of record for the whole of Switzerland from 1880 to 1954, states that 71 per cent of the year's hail days occur in June, July and August, 16 per cent in May, and 9 per cent in September.[9] Finally, in the Colorado State University network of North-eastern Colorado, 40 of the 76 days from May 15 to July 31, 1961, had hail. Nine of these were in late May, seventeen in June and fourteen in July.[10]

Since only the Colorado hail belt is available for any analysis involving actual dates of hail days, and the number of days with hail reports is not large, it was decided not to perform any persistence tests on the Colorado data.

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[7] Ibid, pp. 6-7.

[8] Hitschfeld, W., and Douglas, R.H., "Three-Dimensional Radar Patterns Related to Surface Hail Reports", Abstracts of the Sixth Weather Radar Conference, Bull. Amer. Met. Soc., Vol. 38, No. 2, February 1957, p. 99.

[9] Hail Insurance in Switzerland, 1880-1954, The Swiss Hail Insurance Company, 1955.

[10] Schleusener, R.A., and Grant, L.O., Characteristics of Hailstorms in the Colorado State University Network, 1960-61, Atmospheric Science Technical Paper No. 20, Civil Engineering Section, Colorado State University, Fort Collins, Colorado, October 1961.

Duration of Hailfall

Data on hailfall duration at a point are rather scarce, but some values are available from other parts of the world. However, little detailed investigation of the relations of duration to maximum hail size, season, geographical location, etc., as performed on Alberta Hail Studies data in this thesis, has been conducted. In his paper on the Transvaal storms of January 15 and 16, 1964, Carte states that "most other storms in this area which have been analysed have shown a marked trend of increasing duration with increasing size of hailstones".[11] Beckwith, on the other hand, reviews reported durations in the Denver network by saying that "no particular size pattern follows the duration of hailfall, nor does intensity of accompanying rain correlate".[12] The more complete Alberta Hail Studies data suggest that duration of hailfall is longest in more severe years and in the high-activity months of July and August. These two months have been shown in Chapter VIII to have the highest percentages of large hail in Central Alberta, and thus there is some evidence of a relation between hailfall duration and maximum stone size.

Table XV summarises the duration data which the writer has found in the literature. The information for England is taken from an article by Crossley,[13] but the remainder is from the various reporting networks referred to in this chapter. Colorado and Alberta record similar hailfall durations, several minutes longer on the average than in the other areas. They also occupy very similar positions in relation to the Rocky Mountains.

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[11] Carte, A.E., Hailstorms in Johannesburg, Pretoria and Surroundings on January 15 and 16, 1964, CSIR Research Report 228, Pretoria, South Africa, 1964, p. 7.

[12] Beckwith, Characteristics of Denver Hailstorms, op. cit., p. 23.

[13] Crossley, A.F., "Hail in Relation to the Risk of Encounters in Flight", Met. Mag., Vol. 90, No. 1065, April 1961, pp. 101-110.

TABLE XV - HAILFALL DURATION IN VARIOUS REGIONS

Region	No. of Reports	Period Covered	Frequency Distribution	Median Dur. (minutes)
Bedfordshire, England	251	Unspec-ified	50% of falls 3 min. or less and 2% over 30 min.	2
New England[14]	232	Three unspec. summers	Range is from 0 to 25 min.	3-4
Denver	450	1949-55	From 10 sec. up to 45 min. Reports up to 15 min. common	5
N.E. Colorado	276	1960	60% shorter than 15 min.; 15% longer than 25 min.	10-15
N.E. Colorado	328	1961	68% shorter than 15 min.; 8% longer than 25 min.	5-10
Central Alberta	28,577	1957-66	73% shorter than 12 min.; 7% longer than 25 min.	7-12 (Mean 10)

Duration decreases away from the Divide in Alberta, but even 200 miles away the average is still eight minutes. Hence it seems that in North America hailstorms originating in mountain country and travelling over high ground in the continental interior are the most severe in terms of hail duration at a point.

Probably this is a function of the rapid ground heating at higher altitudes, and the lower position of the freezing level and tropopause relative to the ground. Lapse-rates thus tend to be steeper than over lower terrain, promoting more intense and sustained convective processes. Also, Blackmer points out that in the American mid-west "preliminary evidence indicates that hailstorms which move across level terrain or upslope produce less damage than hailstorms which move downslope".[15]

[14] Donaldson, R.J., Chmela, A.C., and Shackford, C.R., "Some Behaviour Patterns of New England Hailstorms", in Weickmann, H. (ed.), op. cit., pp. 354-368.

[15] Blackmer, op. cit., p. 21.

Alberta and Colorado storms generally have a downslope component of motion for very long distances.

Onset Time of Hail.

Onset time has been reported by many authors in their individual studies of large storms,[16] but no coherent pattern could be expected to emerge from these. The only information of any quantity that the writer has been able to find is from the Denver area and Northeastern Colorado.

Beckwith has given histograms of onset times for 829 hail reports amassed over the ten years 1949-58 in the Denver network.[17] The mode is the hour from 1500 to 1600 MST, but there is no really sharp peaking. However, 56 per cent of the reported starting times lie between 1400 and 1700 MST. Data of onset times are also available from the Colorado State University network in Northeastern Colorado for the years 1960 and 1961, with 278 and 344 reports respectively.[18] Again there is no sharp peaking; 1700-1800 MST was the modal hour in 1960, compared with 1500-1600 MST in 1961, but in both years the greatest concentration of starting times was in the three hours 1500-1800 MST. Sixty per cent of reported hailfalls in 1961 began between these times. The corresponding value in 1961 was 48 per cent. On the average, then, hailfall in Northeastern Colorado begins somewhat later in the day than in the immediate vicinity of Denver.

Some seasonal variation of onset times is recognised in the North-

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[16] For instance, there is an account of a rare severe storm in Florida, which dropped golfball-size hail on the Pompano Beach district around 2000-2100 EST on January 21, 1957. See Hiser, H.W., "Radar Analysis of Two Severe Storms in South Florida", Bull. Amer. Met. Soc., Vol.39, No. 7, July 1958, pp. 353-359.

[17] Beckwith, Analysis of Hailstorms in the Denver Network, 1949-58, op. cit.

[18] Schleusener and Grant, op. cit.

eastern Colorado study. Unfortunately, only data from May, June and July of the second season are presented, so that the realisation of an areal variation is perhaps of more interest to the present work. Schleusener and Grant remark on the tendency for hail onset to be later in eastern than in western districts in May and June. This trend is not visible in the reports from July, but since only 81 observations are available for this month, compared with 271 for May and 253 for June, the July data may constitute an inadequate sample. The evidence for onset times becoming later from west to east in Northern Colorado is further substantiated by Beckwith's mention of forty hail reports received from between Denver and the Front Range of the Rockies 20 miles west of the city. The modal hail onset in these reports is still earlier than in the Denver network itself.

It is possible to account for this feature in terms of the same "distance from the Divide" distribution already described for Central Alberta. Figure 32 shows the relation of the Colorado hail-reporting networks to the mountains. In Northern Colorado the Great Divide may conveniently be represented by the north-south line on the map. Approximate distances from the Divide to Denver and to significant sections of the Northeastern Colorado network are also marked.

Table XVI (after Schleusener and Grant) shows the most common hour reported for onset times of hailfall in the two zones of the Colorado State University network indicated in Figure 32. The May and June hours of most common onset coincide quite well with those reported in Central Alberta at these distances from the mountains (see Figure 20). In Central Alberta the mean starting time of hailfall 100-130 miles from the Divide is from about 1625 to 1645 MST, very slightly later than at the same distances in Northern Colorado. At 155-185 miles it is from 1650 to 1700 MST on the curve of Figure 20, while the point scatter is from 1625 to 1745

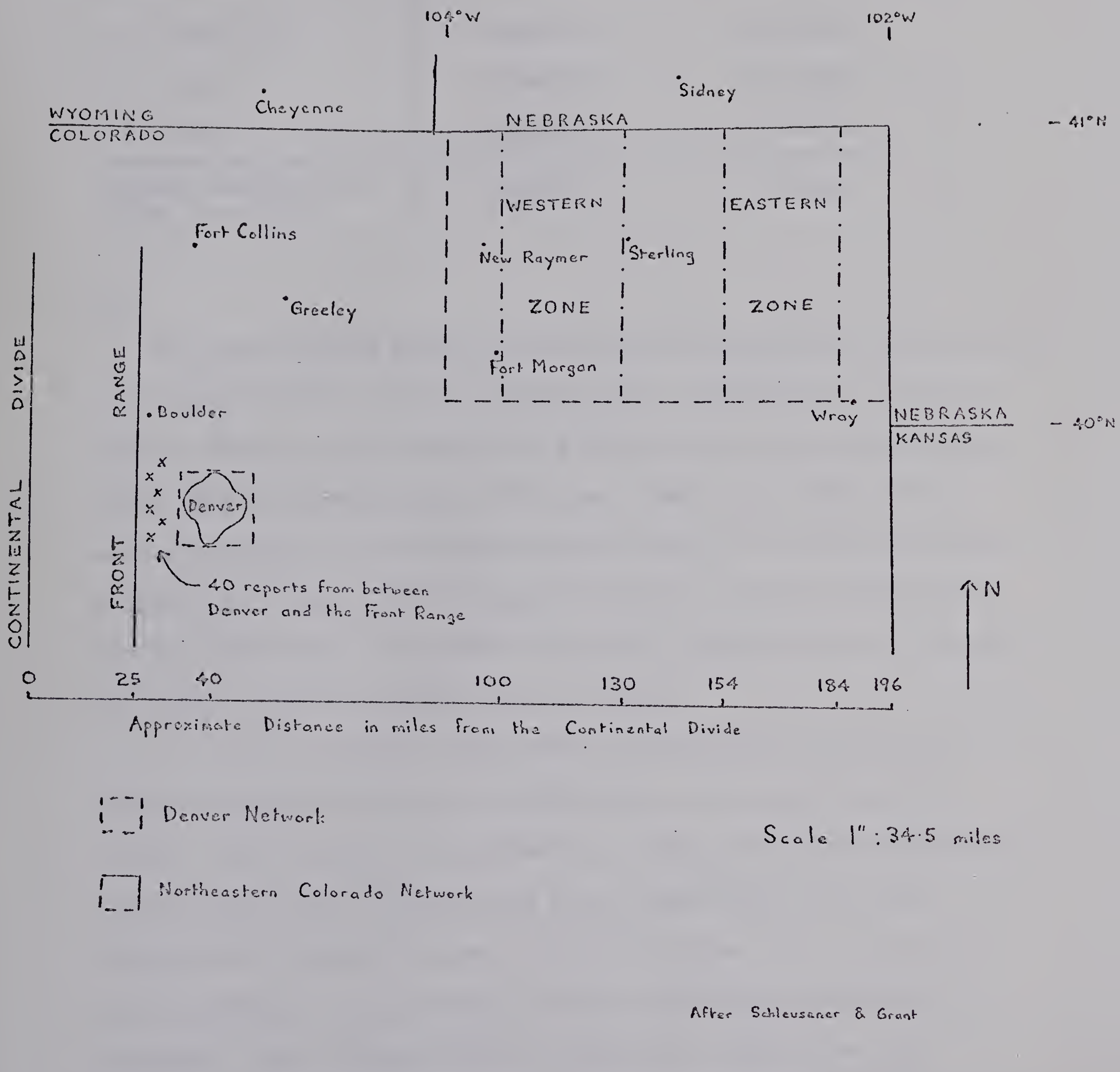

FIGURE 32 - LOCATION OF COLORADO HAIL REPORTING NETWORKS

TABLE XVI - MOST COMMON HOUR OF HAIL ONSET (MST) IN NORTHEASTERN COLORADO

Period	Western Zone	Eastern Zone
May 15-31	1600-1700	1700-1800
June	1500-1600	1700-1800
July	1700-1800	1500-1600
Approx. distance in miles from Divide	100-130	154-184

MST.

The Denver results given by Beckwith have a considerably earlier modal hour, 1500-1600 MST. The only Alberta reports comparable with the forty cited by Beckwith 25-30 miles from the Divide are in the composite group with a weighted mean distance of 33 miles. Their onset times are no earlier than those of the 40-mile group in Alberta, but they do show the secondary peak around 1800 MST noted by Beckwith in reports close to the Colorado Front Range. In Alberta this peak is visible as far as 55 miles out, where it occurs some 30-45 minutes later.

In summary, it appears that Alberta and Colorado hailfalls show a similar retardation of onset time with distance from the Continental Divide. From theoretical considerations, however, the Alberta distribution might be anticipated displaced some forty minutes later in the day. Although both areas are located in the Mountain Time Zone, sun time is later in Alberta than in Colorado due to a ten-degree difference in longitude. Since Colorado data are given to the nearest hour, the displacement suggested is too small to be evident in this study even if it exists.

Maximum Size of Observed Hail

Hailstones themselves are a rather more concrete feature of a hailfall than its duration or starting time, and information on maximum sizes is correspondingly easier to find. Unfortunately, though, reports of stone size are almost all in terms of "familiar" objects associated subjectively with certain ranges of magnitude. The objects referred to are not the same the world over, nor are they all universally known.[19] The same objects are even regarded as having different dimensions by different analysts. Figure 33 summarises some of the size-reporting schemes in use. With the exception of Feteris,[20] the sources are all articles already referred to in this chapter. Besides all the categories listed in Figure 33, the writer has also found references to hailstones the size of eggs,[21] and grapefruit.[22]

A comparative study of hailstone maximum sizes, then, is likely to be fraught with difficulties. Some attempt has to be made to convert to a standard dimensional system. Differing class boundaries make it impossible to compare maximum size distributions effectively even when the distorting effect of a varying category width has been eliminated by weighting, as was done by Donaldson, Chmela and Shackford.[23]

An universal system with equal class intervals and the same class

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[19] Cricket and baseball, for instance, are games restricted to certain limited areas of the world.

[20] Feteris, P.J., "Statistical Studies on Thunderstorm Situations in the Netherlands", J. Appl. Meteor., Vol.4, No. 2, April 1965, pp. 178-185.

[21] Smith, D.P., "A Thunderstorm High Over England", Met. Mag., Vol. 90, No. 1064, March 1961, pp. 74-78.

[22] Ward, N.B., The Newton, Kansas, Tornado Cyclone of May 24, 1962, Proceedings of the 1964 World Conference on Radar Meteorology and the Eleventh Weather Radar Conference, Boulder, Colorado, September 14-18, 1964, pp. 410-415.

[23] Donaldson, Chmela, and Shackford, op. cit.

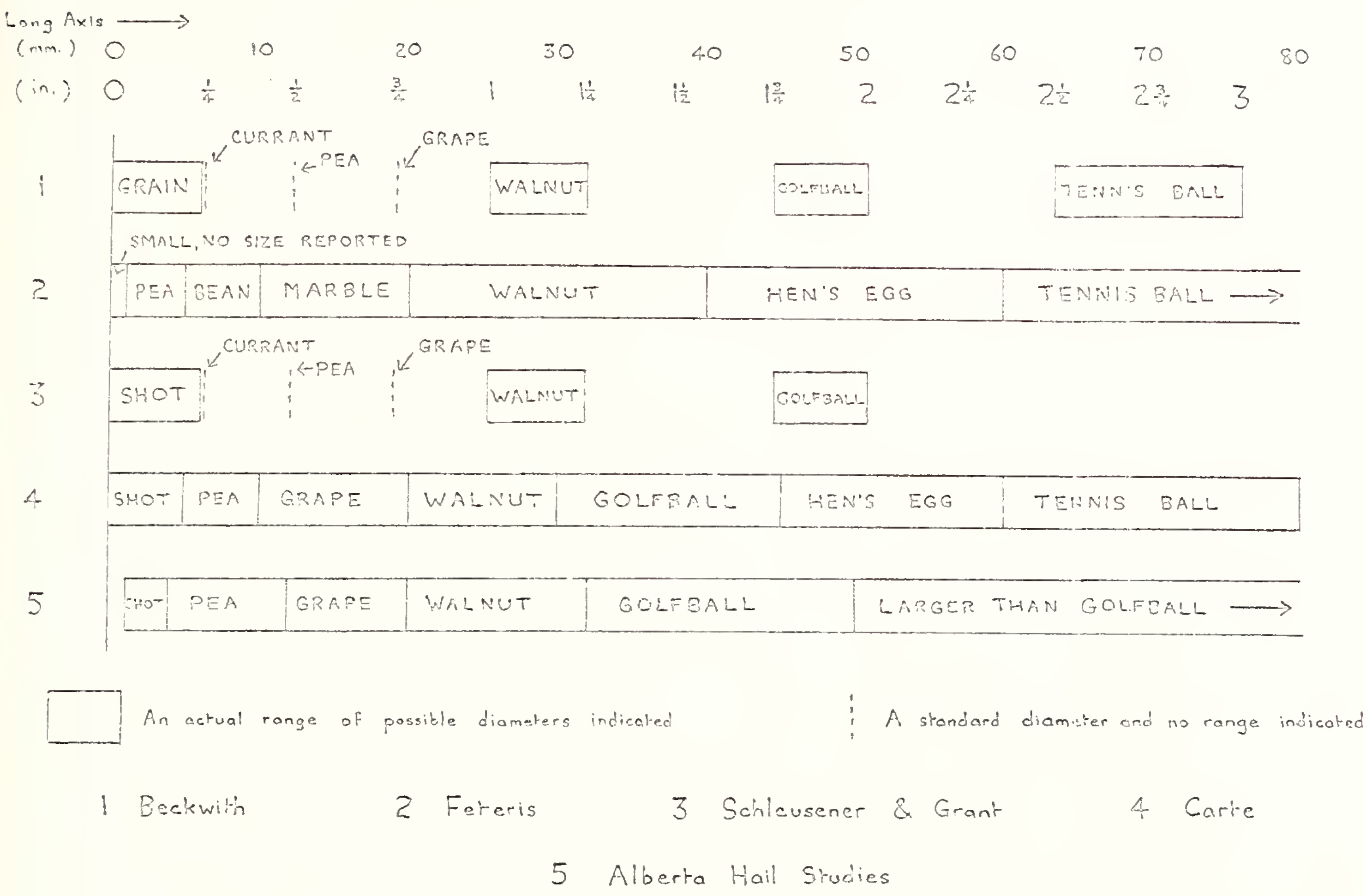

FIGURE 33 - SOME SIZE SYSTEMS PRESENTLY IN USE

boundaries - grouping into 0.5 cm. intervals has been used by Douglas[24] - is desirable. However, with a first approximation to most of the systems presently in use, it is possible to sort sizes into three categories, 0-9, 10-30 and 31 and more millimetres in diameter, and attain some measure of consistency.[25] Thus in the Transvaal and Central Alberta, stones of shot and pea size may be regarded as less than 1 cm. in diameter, while in Denver and Northeastern Colorado, this class will include shot and currant sizes. Table XVII is a summary of maximum hail size frequency distributions in various parts of the world, derived in the manner described.

TABLE XVII - REGIONAL VARIATION OF PERCENTAGE FREQUENCIES OF MAXIMUM OBSERVED HAIL SIZE

Region	No. of Reports	Period Covered	Source	Percentage frequencies of diameter (cm.)		
				0-1	1-3	3+
N.E. Colorado	506	1960-61	Schleusener and Grant	16 (34)	75 (57)	9
Denver	829	1949-58	Beckwith[26]	23 (44)	73 (52)	4
Central Alberta	29,408	1957-66	Alberta Hail Studies	48	46	6
Transvaal	4,812	1962-65	Carte[27]	56	40	4
New England	317	Three unspec. summers	Donaldson, Chmela and Shackford	60	36	4
Illinois	267	1958	Blackmer	65	34	1

[24] Douglas, R.H., Size Distributions of Alberta Hail Samples, Stormy Weather Research Group, Scientific Report MW-36, McGill University, Montreal, August 1963, p. 58.

[25] Carte, A.E., and Kidder, R.E., "Transvaal Hailstones", Quart. J. Roy. Met. Soc., Vol. 92, No. 393, July 1966, pp. 382-391.

[26] Beckwith, Analysis of Hailstorms in the Denver Network, 1949-58, op. cit.

[27] Carte, Hailstorms in South Africa, op. cit.

Both Colorado networks define "peas" rather larger than do any of the others. Peas are more or less the same size everywhere, and it may be that an appreciable number of the pea-size reports in Colorado should in fact be included in the "below 1 cm." category. The figures in parentheses in Table XVII are the percentages resulting from the assumption that this "appreciable number" is in fact one half of the pea-size reports. Colorado frequency distributions are thus brought more into line with those of the rest of the world.

In summary, more than 50 per cent of reports from the High Plains hail belt of North America mention at least some stones larger than 1 cm. in diameter. Within this belt, Colorado hail is probably larger on the average than that in Central Alberta. Transvaal and New England have some stones greater than 1 cm. in 44 and 40 per cent of their hail reports respectively. In Illinois, at least in 1958, only 35 per cent of reports had hail larger than 1 cm., and only 1 per cent had hail over 3 cm., compared with at least 4 per cent in all the other areas.

Brooks has given details of 509 reported hailfalls in India, 16 per cent of which had hail over $1\frac{1}{2}$ inches in diameter. However, he states that "many lesser storms probably escaped notice"[28], so that even here, where hailfall is frequent and notably severe, the maximum size distribution likely corresponds closely to those presented in Table XVII. Large hail is reported from time to time even in areas where hailstorms are relatively infrequent. On March 29, 1963, hail up to at least three inches in diameter fell over Miami, Florida.[29] Hailstones an inch in diameter

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[28] Brooks, C.E.P., Letter to the Editor, Quart. J. Roy. Met. Soc., Vol. 70, No. 304, April 1944, p. 227.

[29] Neumann, C.J., "Mesoanalysis of a Severe South Florida Hailstorm", J. Appl. Meteor., Vol. 4, No. 2, pp. 161-171.

have been experienced in Bermuda,[30] and in Southern Oregon,[31] neither area being known for high hail severity. It would seem likely, therefore, that maximum size distributions, in view of all the information reviewed here, do not vary very widely throughout the world.

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[30] Jones, E.C., "Freak Hail Storm", Weather, Vol. 21, No. 6, June 1966, p. 210.

[31] Decker, F.W., and Calvin, L.D., "Hailfall of 10 September 1959 Near Medford, Oregon", Bull. Amer. Met. Soc., Vol. 42, No. 7, July 1961, pp. 475-480.

CHAPTER X

CONCLUSION

Summary

Thirty thousand IBM punched cards of individual hail reports from 1957 to 1966 form a more than adequate basis for a climatological examination of hailfall in the project area. This thesis performs such a study, with both geographical and temporal emphases.

Variations of particular hailfall parameters over the area and through the period 1957 to 1966 have been discussed in individual chapters. This summary attempts to extract some apparent relations among the parameters themselves, and to bring out some of the more important points made in earlier chapters.

Over the whole area in any given period, the numbers of hail days, major hail days and unsolicited reports are mutually related; and the diurnal concentration of hail onset times becomes sharper with increasing maximum hail size. But most other associations are not so general. Examination by year finds onset time is earlier when the totals of hail days and unsolicited reports are larger; seasonal investigation shows the opposite tendency. Geographical analysis also fails to show consistency. Mean onset time and frequency index show a similar trend away from the mountains, but overall spatial analysis (Figures 13 and 19) reveals rather less correlation in other directions.

Mean duration is longer in years with higher hail day and unsolicited report totals, but the same relation does not hold from month to month. And although duration does decline somewhat with increasing distance from the Divide, in similar fashion to hail frequency, general spatial analysis fails to show a convincing relation with frequency. The Large Size Ratio, on the other hand, bears no overall relation to distance from the Divide,

but its geographical distribution shows some correlation with that of mean duration (Figures 24 and 28). It is apparently not related to the numbers of hail days or unsolicited reports in a given period; August has the highest Large Size Ratio, but only about half the unsolicited reports of June or July.

The stretch of country from Red Deer to Camrose has already been referred to (p. 56). It has higher durations and Large Size Ratios, together with later onset times, than the surrounding country, but does not have high Frequency Indices. The feature may thus be the result of a small number of fairly severe storms developing late in the day and following this track.

Conclusions regarding the inter-relation of the various parameters must make the Rocky Mountains the linking factor. Mean hail onset, mean duration and hail frequency all show an overall change with increasing distance from the Continental Divide. In many cases tha annual and seasonal analyses show rather indeterminate inter-relationships, and the same is true of the general spatial analysis. The mountain-oriented study gives more consistent and convincing results. This suggests that the values of the various hail parameters are related to one another through the position of the hailfall relative to the mountains rather than by the period in which they occur. In other words, the location factor is very significant.[1]

Slight evidence exists in the form of the curves for some of the hailfall properties plotted against distance from the mountains (Figure 34)

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[1] This argument is partially supported by Powell's survey of hail frequency in Alberta for the ten years 1951-60, which demonstrated almost the same areas of high hail frequency as those shown for 1957-66 in Figure 13 of this study. See Powell, G.L., The Relationship of Physiography to Hail in Alberta, unpublished M. Sc. thesis, University of Alberta, Edmonton, 1961.

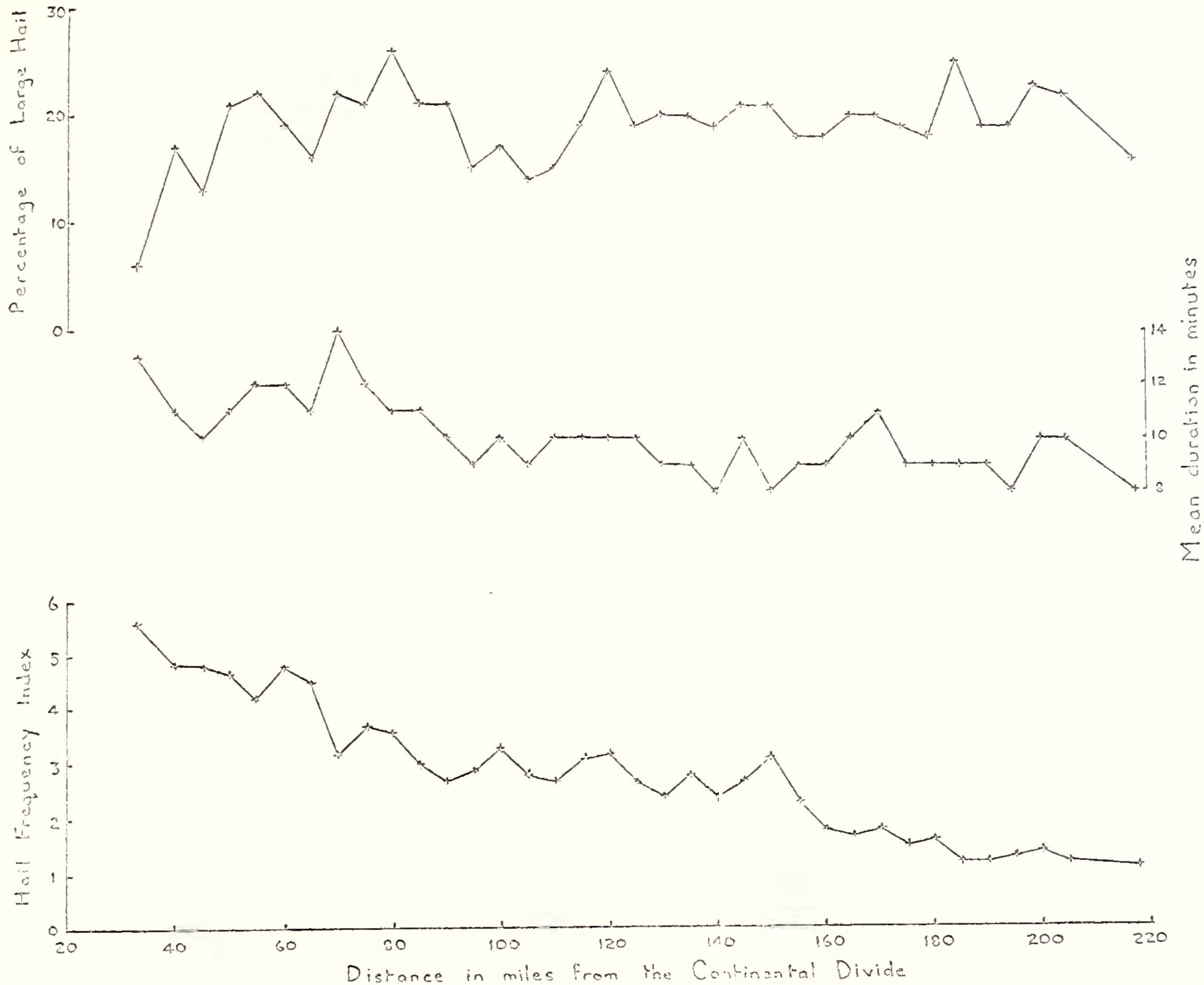

FIGURE 34 - LARGE HAIL RATIO, MEAN DURATION AND HAIL FREQUENCY INDEX VERSUS DISTANCE FROM THE MOUNTAINS

that there may be a wave-type variation, with a wavelength of about 40 miles.[2] Finally, a comparison of Alberta Hail Studies data with those from other parts of the world showed that the hailfalls of Colorado are the most similar to those experienced in Central Alberta.

<u>Towards a Hailstorm Model for Central Alberta</u>

The findings of this thesis are essentially climatological, and without a concurrent study of all other hail data can make only a tentative indirect contribution towards the formulation of a hailstorm model for the region. Certain inferences may be drawn. But first it is necessary to attempt a brief review of models already put forward, that these inferences may be fitted into the general picture.

Browning,[3] and others, have stated that the simple model proposed by Byers and Braham in 1949,[4] while an admirable hypothesis for the single short-lived convective cell of non-severe proportions, is not applicable to the long-lasting severe travelling storm. Browning and Ludlam have suggested a model of the self-sustaining "supercell", based on a tilted updraught and downdraught adjacent to one another and persisting uniformly for quite a considerable length of time, with strong wind shear at all

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[2] It has been suggested that there may be some relation between the hump of the lee wave caused by the Colorado Rockies and the generation or rejuvenation of convective cells. <u>See</u> Macdonald, N.J., and Harrison, H.T., "Some Observations of the Mountain Wave in Eastern Colorado", <u>Bull. Amer. Met. Soc.</u>, Vol. 41, No. 11, November 1960, p. 627.

[3] Browning, K.A. (ed.), <u>A Family Outbreak of Severe Local Storms - a Comprehensive Study of the Storms in Oklahoma on 26 May 1963</u>, Part 1, Special Report No. 32, Air Force Cambridge Research Laboratories, L.G. Hanscom Field, Bedford, Massachusetts, September 1965.

[4] Byers, H.R., and Braham, R.R., Jr., <u>The Thunderstorm</u>, U.S. Government Printing Office, Washington, D.C., 1949.

levels;[5] this model was further refined in a three-dimensional framework by Browning,[6] in order to account for the movement of the storm to the right of the steering winds in the Northern Hemisphere. The Wokingham, England, storm on which this model was originally based was noteworthy for the consistency of its severe hail production over a long period.

Carte, however, has studied a severe storm in South Africa, and was impressed by the changing intensity and even intermittency of hail laid down at the ground, together with the rather modest winds at all levels.[7] Detailed analysis led him to the conclusion that the precipitation pattern resulted from the movement of many individual cells travelling at a small angle across the axis of the main storm track. He postulated near-vertical updraughts, ultimately extinguished by the release of precipitation from each cell. The storm was thus visualised as a composite of many cyclical cell developments. That large hail may form rapidly enough to be generated in a single cell appears possible.[8] However, by permitting the simultaneous existence of more than one cell, in different stages of development, Carte's picture allows for the "looping", or sequential encounters with a number of

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[5] Browning, K.A., and Ludlam, F.H., "Airflow in Convective Storms", Quart. J. Roy. Met. Soc., Vol. 88, No. 376, April 1962, pp. 117-135.

[6] Browning, K.A., "Airflow and Precipitation Trajectories Within Severe Local Storms Which Travel to the Right of the Winds", J. Atm. Sci., Vol. 21, No. 6, November 1964, pp. 634-639.

[7] Carte, A.E., "Features of Transvaal Hailstorms", Quart. J. Roy. Met. Soc., Vol. 92, No. 392, April 1966, pp. 290-297.

[8] Recent work by the Stormy Weather Group at McGill University in Montreal suggests that under certain conditions (specifically those commonly found in Alberta) large hail may form in a few minutes in a single cell. As early as 1964, Srivastava was able to state that "it is possible for precipitation particles of appreciable size to appear rapidly at all levels as seems to be required by observations of rapid growth of first radar echo in convective clouds". See Srivastava, R.C., A Model of Convection With Entrainment and Precipitation, Stormy Weather Research Group, Scientific Report MW-38, McGill University, Montreal, October 1964, p. 89.

updraughts, traditionally regarded as necessary for the growth of large hailstones.

In this context, Russian workers in the Caucasus have concentrated specifically on the environment of the growing hailstone.[9] They concluded that the growth largely occurs in an "accumulation zone" of high supercooled liquid water content. This zone or "hail centre" is found in the vicinity of the maximum updraught in the cell and appears capable of producing large hail in the short times observed for many hail cells. The updraught is regarded as increasing almost linearly with height to a maximum and then decreasing in the same fashion to the cell-top. This concept has been utilised in the work of the Stormy Weather Research Group, together with the mechanism of spongy growth of hail,[10] to develop the model of rapid hail growth in intense convective cells in Alberta.

The role of strong wind shear in the development of a severe storm has been a topic of some controversy. Dessens has put forward the view, after a statistical analysis of thunderstorms in southwestern France,[11] that convection in the absence of strong wind shear leads to vertical "chimneys" very similar to the simple model of Byers and Braham. These are therefore short-lived and not usually severe. Strong shear, on the other hand, tends to tilt the "chimneys" so that the updraught is not suppressed by the

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[9] Sulakvelidze, G.K., Results of the Caucasus Anti-Hail Expedition of 1965, translated by the National Council for Atmospheric Research, Boulder, Colorado, from Vysokogornyi Geofizicheskii Institut Trudy, Issue 7, 1966, pp. 1-61.

[10] Samples of walnut-size hail falling in Central Alberta in 1967 showed 11 to 17 per cent of the stones to consist of still unfrozen water. This is a larger percentage than has so far been detected elsewhere, in places such as Colorado, South Dakota and Kenya. See Alberta Hail Studies Weekly News Report, No. 67-9, July 31, 1967.

[11] Dessens, H., "Severe Hailstorms are Associated With Very Strong Winds Between 6,000 and 12,000 Metres", in Weickmann, H. (ed.), Physics of Precipitation, Baltimore, Waverly Press, 1960, pp. 333-336.

fall-out of precipitation. The storm is thus stabilised and persistent, differing only slightly in concept from the "Browning Supercell". But Newton has also considered the case of strong wind shear, and arrived at a multicellular storm structure similar to the one proposed by Carte (and discussed previously) for a situation where such a wind shear was not present:

> "With strong vertical shear and pronounced veering of wind with height, growth of new convection is most favoured on the right flank of a rainstorm. Since young cells have most intense vertical motions, large hail should tend to occur predominantly on that flank. The hail track should have restricted width compared with the track of the rainstorm as a whole." [12]

Ratner, however, has investigated 1958 U.S. upper air data and concluded that severe hail production in American storms is not always associated with strong shear.[13]

In this rather confusing picture a place must be found for the Alberta hail climatology reviewed in this thesis. It is obvious that the position of the hail belt in the lee of the Rocky Mountains is of tantamount importance to any storm model. The foothills zone is the major source region; most of the parameters analysed show some relation to distance from the Divide. Considerable similarity to Colorado hail incidence has been demonstrated. This suggests that models may be interchangeable between the two areas. For example, it has been found that summer hailfalls in the lee of the Rocky Mountains of the United States are five to fifteen times more intense than those in the Middle West.[14] The same kind of association of

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[12] Newton, C.W., "Morphology of Thunderstorms and Hailstorms as Affected by Vertical Wind Shear", in ibid, pp. 339-346.

[13] Ratner, B., "Do High-Speed Winds Aloft Influence the Occurrence of Hail?", Bull. Amer. Met. Soc., Vol. 42, No. 7, July 1961, pp. 443-446.

[14] Changnon, S.A., Jr., and Stout, G.E., "Crop-Hail Intensities in Central and Northwestern United States", J. Atm. Sci., Vol. 6, No. 3, June 1967, pp. 542-548.

hailfall intensity with distance from the mountains seems to be present in Central Alberta.

There is slight evidence that the lee wave effect is visible in the observed Alberta hail patterns. Cunningham says of Colorado:

> "mountain wake circulations may be of importance here; that is, the large storms first develop in and under a region of general upward motion in the first downstream wave beyond the mountain. Once started over flat terrain, these storms, on drifting eastward, can apparently become organised enough to outweigh the effects of the further downstream portion of the mountain wave." 15

He goes on to describe the Colorado storm under review in terms of a system on the scale and behaviour pattern of the "Browning Supercell":

> "the intent...is to point out that some large Cumulo Nimbus may not consist entirely of a series of cellular elements in various stages of their life cycle, but may to some extent consist of a steady horizontal and vertical circulation system." 16

The nature of this comment suggests that both multicellular and "steady" hailstorms are recognised in Colorado.

In Alberta, the work of Powell on the geographical irregularity of hail frequency supports the validity of the large local variations of some hailfall properties found in this study, and suggests that physiography may play a considerable part in the overall hailstorm pattern of the area.[17] This role may be in providing localised regions favourable to both the formation and rejuvenation of storms, which thus tend to be multicellular. Alberta hailstorms, for the most part, persist for at least an hour. Therefore they cannot be explained in terms of the simple Byers and Braham model. Also their hail production is by no means uniform throughout their life, and a multicellular structure would help to account for this feature.

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[15] Cunningham, R.M., "Hailstorm Structure Viewed From 32,000 Feet", in Weickmann, H. (ed.), <u>op. cit.</u>, p. 325.

[16] <u>Loc. cit.</u>

[17] Powell, <u>op. cit.</u>

Finally, the concentration of hail onset times for Alberta into the afternoon and early evening, particularly for larger hail, suggests that a diurnal growth pattern must form the basis of any general model. This may, of course, take into account the passage of fronts and upper level troughs (synoptic situations favourable to hailstorm development in the area). If these pass at the requisite time of day they may accentuate the diurnal cycle, but at night or in the early morning these situations fail to produce major hail.

This idea of a predominant diurnal cycle of hail formation is perhaps best summarised by Beckwith. He referred, and on the basis of rather sparse climatological data, to storms in Colorado, but all the features he mentions have been found applicable in the present study to Central Alberta hailfall. The writer regards Beckwith's views, even after ten years, as an excellent summary of the known features of the diurnal hailstorm pattern in the lee of a high mountain range.

> "It has been well established that the 'chimney effect' of the heated surfaces of the foothills accelerates the initial thunderstorm formation. Eastern and southern faces of the mountains in the Front Range breed thunderstorms usually by early afternoon. Under the typical hail circulation pattern these thunderstorms drift eastward or northeastward and continue to develop as they move out on the heated Plains....A secondary peaking of activity in the mountains in early evening is probably the result of delayed thunderstorm development above the heated western slopes in mid or later afternoon. Generally these thunderstorms decay east of the foothills, since by this time there lacks the added thermal lift of the Plains, which perhaps have even been chilled by earlier shower activity." 18

Suggestions for Further Research

Some of the hailfall properties reported on the farmer hail cards were not dealt with in this thesis. They will bear further work and would aid towards a theory of hailstorm development in

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[18] Beckwith, W.B., "Characteristics of Denver Hailstorms", Bull. Amer. Met. Soc., Vol. 38, No. 1, January 1957, p. 27.

Alberta. They include hailfall intensity, rain-hail sequence and soft hail occurrence.[19] A rough estimate of the ice mass deposited on unit area at the ground may be arrived at indirectly from the most common size of hail observed and the spacing or depth of hail. An intensity index with ten values, each corresponding to an order of magnitude, has been derived for use with Alberta Hail Studies reports. The rain-hail sequence at a point is another vital parameter which would have to be taken into account in any storm model.

The work undertaken in this study must be regarded merely as a preliminary investigation. Very little in the way of statistical significance testing, for instance, has been performed on the computer output. Correlation tests on some of the associations proposed would be a logical next step.

The fact that the data are stored on IBM cards facilitates rapid processing. So far, only 46 of the 80 columns on each card have been utilised, so that there is a possibility of punching further information into the remainder. Synoptic data, echo-top height and altitude above sea-level of the reported hail occurrences are three factors that spring readily to mind and could easily be incorporated into the punched cards. Alternatively, hail activity indices might be punched on the "Climat 7" cards of the relevant upper air conditions at Edmonton and Calgary,[20] perhaps in place of the data on the second tropopause. In any case, there is potential for rapid analysis of further features of both hail

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[19] Analysis of soft hail reports is being undertaken by Alberta Hail Studies at the present time, in conjunction with the study of freezing conditions in Alberta hailstorms being conducted by the Stormy Weather Group at McGill University.

[20] Upper air data from radiosonde stations operated by the Meteorological Branch of the Department of Transport are available on punched cards known as "Climat 7" cards.

climatology and meteorology and their inter-relations. These relationships will bear much more investigation.

An innovation in the 1966 season was the installation of a radiosonde station at the Penhold headquarters of Alberta Hail Studies. This should enable a truer evaluation of upper air conditions in the Red Deer region. Previously these had to be arrived at by interpolation between the data provided by the Meteorological Branch radiosonde ascents at Edmonton and Calgary International Airports. Both are well out towards the northern and southern extremities of the project area, and in each case only two ascents a day are performed.[21]

Many storms already producing considerable hail pass from the unpopulated Rocky Mountain foothills into the western portion of the project area. It is evident from these that much more information is required from this foothill source area of so many Alberta hailstorms. A step forward in 1967 has been the distribution of hail report-cards to the lookout towers of the Alberta Forestry Service. The radar is able to detect and track the storms long before they enter the project area from the west, so that hail reports from the lookout towers can at least be correlated with the radar record. Unfortunately these towers are few in number in a vast expanse of terrain. Much of the foothills country is thickly forested, so that automatic hail recorders or an instrument network would be difficult to site and maintain. However, if some practical and reliable method of recording hailfall in the foothills could be devised, it would aid greatly towards the completion of the picture of hail behaviour in Central Alberta.

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[21] The location of a further radiosonde station in the vicinity of Rocky Mountain House or Nordegg would provide interesting and useful information on the atmosphere of the immediate lee of the Rockies; it seems likely that this may differ, particularly in terms of moisture, from those at other points in the project area.

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HAIL PUNCHCARD CODING SHEET

Column	Code
2	TYPE OF REPORT 1 Mailed in 2 Telephoned in 3 Car survey 4 Telephone survey
3 4	YEAR
5	MONTH 4 April 5 May 6 June 7 July 8 August 9 September 0 October
6 7	DAY OF MONTH (e.g. 03,13, etc)
8 9 10 11	TIME M.S.T. 0000-2359 9999 Missing
12 13 14	DURATION-MINUTES 000-998 999 Missing e.g. (Less than one half min. code 000, five mins., 005)
15	ACCURACY 1 Accurate to one minute 2 Accurate to five minutes 3 Accurate to ten minutes 4 Accurate to fifteen minutes 5 More than fifteen minutes 9 Missing (This question not on most cards)
16 17 18 19	QUARTER (NE,SE,SW,NW) 0 No 1 Yes 9999 Missing
20 21	SECTION 01-36
22 23	TOWNSHIP 16-52
24 25	RANGE 01-99, 10-30
26	INTERMITTENCY 0 Continuous 1 One Burst of hail 2 Two bursts " " 7 Seven bursts " " 8 Unknown no. of bursts or intermittent 9 Missing
27 28	HAIL SIZE 0 Unknown or missing 1 Shot 2 Pea 3 Grape 4 Walnut 5 Golfball 6 Larger
29	HAIL SPACING OR DEPTH 1 Spacing 2 Just covered 3 Depth 9 Missing or melted (Spacing less than 1/2" code 2, just covered) (Few stones, code 999 in cols. 29,30,31) ... 2 in col. 46.
30 31	ACTUAL SPACING OR DEPTH 00-96 Spacing in inches or depth in tenths of an inch 98 Greater than 8 feet 99 Missing or melted (Spacing less than 1/2" code 00)
32	SEQUENCE 1 Hail began before rain 2 Hail began the same time as rain 3 Hail began after the rain 4 Hail only, no rain 9 Missing
33	TIME OF THE LARGEST HAIL 1 At the beginning of hailfall 2 In the middle of hailfall 3 At the end of hailfall 4 Throughout hailfall 9 Missing
34	SOFT HAIL 0 No 1 Yes 9 Missing
35	SIZE OF SOFT HAIL 0 Unknown or missing 1 Shot 2 Pea 3 Grape 4 Walnut 5 Golfball 6 Larger NOTE: (COLS. 34,35 MAY BE 00,10,90,11, 12,13,14,15, or 16)
36	DAMAGE 0 Nil 1 10-30% (Slight) 2 40-70% (Moderate) 3 80-90% (Heavy) 4 100% (Severe) 5 Unknown but mentioned 9 Not mentioned
37	LIGHTNING 0 No 1 Yes 9 Missing
38	HIGH WINDS 0 No 1 Yes 9 Missing
39 40	OTHER HAIL 00 Nil 01-98 Number of quarter sections on which hail is known to have fallen 99 Missing
41 42 43	RAINFALL 000-998 Hundredths of an inch 999 Not mentioned (1/2" coded 050, 1 1/2" coded 150)
44 45	DIAMETER OF LARGEST HAIL 00-98 Tenths of an inch 99 Not mentioned
46	OTHER USEFUL DATA 0 No further information on card 1 Some further information on card 2 Further information on depth, spacing, size or structure of hail on card.
47 to 80	TO BE ASSIGNED

APPENDIX B

NETWORK HAIL DAYS AND MAJOR HAIL DAYS

May

Major Hail Days underlined

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
1957																															
1958																															
1959								1																1				4			
1960																															
1961														1													10		10	1	1
1962										1	2	1		1		1												3	20	4	38
1963								1	2	6	3	1												1	8			1			2
1964		3			1					1			1								5	1		1	2						
1965				1									1	2		3		1				1	1			1	2		<u>90</u>	<u>102</u>	10
1966																					12	12					1	32	42	11	15

June

Major Hail Days underlined

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1957				4	27				1	3	1	27	12	16	30	3	3	14	31	8	8		1	<u>373</u>		<u>64</u>	<u>157</u>	<u>114</u>	<u>107</u>	28
1958		1	11	1	2		1	7	2				1	<u>64</u>	3	2	45	1		3	2	<u>54</u>				19	32	35	5	55
1959		2	3		2	<u>173</u>	3	2	<u>114</u>	18		<u>68</u>	<u>163</u>	30	20	12	10	1				<u>158</u>	<u>79</u>	<u>239</u>	13	1			22	<u>196</u>
1960			3	2	1	<u>113</u>		8			4			3	2	<u>163</u>	5		11	<u>56</u>	3	1	2	<u>300</u>	<u>526</u>	7	6	12	1	
1961				1	2	2	6									<u>63</u>	15	5	<u>121</u>	<u>65</u>	2		3			<u>170</u>			6	8
1962	1		2	28	8			<u>150</u>	28	<u>555</u>	7	24	2		11	<u>56</u>	<u>97</u>	7	<u>449</u>	<u>236</u>	<u>50</u>	3			7	49		1		<u>72</u>
1963	1	1					4	6	<u>257</u>	18	1	5			3	7	17	3	<u>55</u>	<u>121</u>	3	1		8	29	10	<u>85</u>	<u>86</u>	3	1
1964				1	35	14	9		1		1	1	<u>48</u>	12	42	2		6	5	38	<u>85</u>	3	<u>47</u>	<u>163</u>	2	3	33			<u>147</u>
1965	5					35	4						5	<u>51</u>			28	23	<u>173</u>	<u>58</u>	<u>126</u>			37			5	2	4	3
1966				10	<u>55</u>		1	25		<u>65</u>	<u>73</u>	18		<u>57</u>	4	1	16		<u>73</u>	<u>64</u>		<u>73</u>	5	3	<u>90</u>		10		3	2

July

Major Hail Days underlined

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
1957	<u>175</u>	5	36		38	<u>149</u>	<u>55</u>	2			4	2	1	23	11	<u>71</u>	4	1	5		35		<u>126</u>	2	5	<u>479</u>	<u>79</u>	3	21	<u>60</u>	<u>90</u>
1958	4	4	<u>95</u>	3		6				20	32	31	3	6	9	11				5		2	3		3		1	1			47
1959	5	<u>92</u>	<u>196</u>	2	3		17		11				21	1	2			2	8	<u>93</u>					1	8	<u>458</u>	19			
1960	20	2	<u>57</u>					18	23	<u>95</u>			1	<u>253</u>	46	17		2	<u>38</u>	<u>224</u>	14	<u>131</u>	<u>86</u>	1							
1961						2	36			1					2	7	1				39		12			9	3		9		5
1962	<u>55</u>	9	<u>63</u>	3	2	11	3	39	30	25		<u>42</u>			2	<u>121</u>	<u>279</u>	3	2	41	1			1	25	<u>549</u>	32	<u>137</u>	1	2	
1963			18	<u>114</u>	<u>140</u>	17	<u>243</u>	<u>86</u>	2	13	1		10	<u>227</u>	15	3	15	1	2		13	4			10	1	2	<u>118</u>	2	<u>157</u>	26
1964	1	2	5	3	<u>95</u>	2			<u>214</u>					4	<u>178</u>	2		<u>279</u>			<u>50</u>	49	3			3	3		2		28
1965		1	16	<u>55</u>	25	<u>93</u>	<u>53</u>	<u>57</u>		27	<u>107</u>	26		15	<u>75</u>	9	<u>173</u>	40		1	<u>103</u>	25	46				<u>38</u>	8	2		
1966		3	37	6	2		<u>219</u>	<u>129</u>	6	<u>129</u>	15		7	3	4	<u>132</u>	8		1	15		32	25		42				<u>262</u>	3	14

August

Major Hail Days underlined

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
1957	12	15	2		1	29	1		2	$\underline{65}$	$\underline{141}$	43		8	4			40	$\underline{103}$	$\underline{96}$	2	1		2		1				4	
1958	2		14				2	5	$\underline{68}$		21		3					1	9		$\underline{53}$	1					1	3	49	1	1
1959	12	$\underline{504}$	4	4			1	32	20	36	1	3			2	31	29	1	1		4	$\underline{175}$	6	9		$\underline{184}$		6			
1960	2		$\underline{61}$	11		1				1	$\underline{68}$	18		21	2	4	1	6	20	4	1		18	6	5	32	3		25		
1961								4							1																2
1962	17	$\underline{107}$		46	14		1	$\underline{73}$	1			10			1		23	17	2		36			1	11	12	5	11	39		
1963	9	26			$\underline{158}$	9	$\underline{309}$						19	$\underline{194}$	$\underline{95}$	1		1	2	8	5	4	1		42	38	3				
1964				17	9				$\underline{260}$				9	9				47			1		3			2		1	31	2	
1965		2	3	5		4			39	$\underline{60}$			1										13	7	9	2	$\underline{159}$	2	1	1	
1966			$\underline{60}$	5	2					33	9				$\underline{38}$	13		13	36								0	14		1	

September

Major Hail Days underlined

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1957																														
1958	$\underline{65}$	2										2					3													
1959					1	35		1											7											
1960																														
1961	6			1	13																									
1962	23									4		3			5														2	
1963		1								1			1				6						4							
1964									4									1		7		1								1
1965	0	11	2	5	15						1							1												
1966	13							8								1												7	1	

Source: Alberta Hail Studies records, 1957-66

Numbers refer to unsolicited reports received for each date.
A "0" means that although there were no unsolicited reports, one or more reports of hail were obtained by survey.
The definition of a major hail day is the same as that given in Footnote #4 of Chapter IV.

APPENDIX C, PART I

PROBABILITY OF HAIL BASED ON THE DAY BEFORE

First Day	Second Day Probability (%)*			
Situation	Situation	June & July	August	June 1–Aug. 31
No Hail	No Hail	47	59	52
	Minor Hail	44	36	41
	Major Hail	9	5	7
	Any Hail	53	41	48
	# of Cases	204	152	356
Minor Hail	No Hail	30	42	33
	Minor Hail	50	48	50
	Major Hail	20	10	17
	Any Hail	70	58	67
	# of Cases	296	134	430
Major Hail	No Hail	14	26	16
	Minor Hail	57	61	58
	Major Hail	29	13	26
	Any Hail	86	74	84
	# of Cases	108	23	131
Any Hail	No Hail	25	39	29
	Minor Hail	52	50	52
	Major Hail	23	11	19
	Any Hail	75	61	71
	# of Cases	404	157	561

* The two-day situation is regarded as belonging to the month in which the first day falls.

APPENDIX C, PART II

PROBABILITY OF HAIL GIVEN THE PRIOR SITUATION OVER TWO DAYS

First Day	Second Day	Third Day Probability (%) Situation	June & July	August	June 1-Aug. 31
No Hail	No Hail	No Hail	48	65	55
		Minor Hail	45	30	38
		Major Hail	7	5	7
		Any Hail	52	35	45
		# of Cases	103	87	190
	Minor Hail	No Hail	24	41	30
		Minor Hail	52	41	48
		Major Hail	24	18	22
		Any Hail	76	59	70
		# of Cases	85	54	139
	Major Hail	No Hail	22	29	24
		Minor Hail	45	71	52
		Major Hail	33	0	24
		Any Hail	78	71	76
		# of Cases	18	7	25
	Any Hail	No Hail	24	40	29
		Minor Hail	51	44	49
		Major Hail	25	16	22
		Any Hail	76	60	71
		# of Cases	103	61	164

First Day	Second Day	Third Day Probability (%) Situation	June & July	August	June 1-Aug. 31
Minor Hail	No Hail	No Hail	43	51	46
		Minor Hail	47	44	46
		Major Hail	10	5	8
		Any Hail	57	49	54
		# of Cases	86	59	145
	Minor Hail	No Hail	34	40	36
		Minor Hail	48	55	51
		Major Hail	18	5	13
		Any Hail	66	60	64
		# of Cases	150	65	215
	Major Hail	No Hail	14	31	17
		Minor Hail	54	46	52
		Major Hail	32	23	31
		Any Hail	86	69	83
		# of Cases	59	13	72
	Any Hail	No Hail	28	38	31
		Minor Hail	50	54	51
		Major Hail	22	8	18
		Any Hail	72	62	69
		# of Cases	209	78	287

First Day	Second Day	Third Day Probability (%) Situation	June & July	August	June 1-Aug. 31
Major Hail	No Hail	No Hail	67	50	62
		Minor Hail	27	50	33
		Major Hail	6	0	5
		Any Hail	33	50	38
		# of Cases	15	6	21
	Minor Hail	No Hail	26	53	32
		Minor Hail	51	40	48
		Major Hail	23	7	20
		Any Hail	74	47	68
		# of Cases	61	15	76
	Major Hail	No Hail	10	0	9
		Minor Hail	71	100	73
		Major Hail	19	0	18
		Any Hail	90	100	91
		# of Cases	31	3	34
	Any Hail	No Hail	21	44	25
		Minor Hail	57	50	56
		Major Hail	22	6	19
		Any Hail	79	56	75
		# of Cases	92	18	110

First Day	Second Day	Third Day Probability (%) Situation	June & July	August	June 1–Aug. 31
Any Hail	No Hail	No Hail	46	51	48
		Minor Hail	44	44	44
		Major Hail	10	5	8
		Any Hail	54	49	52
		# of Cases	101	65	166
	Minor Hail	No Hail	32	43	35
		Minor Hail	49	52	50
		Major Hail	19	5	15
		Any Hail	68	57	65
		# of Cases	211	80	291
	Major Hail	No Hail	12	25	14
		Minor Hail	60	56	60
		Major Hail	28	19	26
		Any Hail	88	75	86
		# of Cases	90	16	106
	Any Hail	No Hail	26	40	29
		Minor Hail	52	53	53
		Major Hail	22	7	18
		Any Hail	74	60	71
		# of Cases	301	96	397

APPENDIX D

EXPECTED AND ACTUAL NUMBERS OF RUNS OF n HAIL DAYS

(i) Expected:

n	Expected number of runs of n hail days										E
	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	
1	11.3	16.1	14.9	16.1	18.1	11.9	12.3	16.6	14.2	15.8	147.3
2	6.6	7.8	7.7	7.8	5.3	7.2	7.3	7.7	7.6	7.6	72.6
3	4.2	3.7	4.0	3.7	1.5	4.3	4.2	3.5	4.1	3.8	37.0
4	2.8	1.8	2.1	1.8	.44	2.5	2.6	1.6	2.3	1.9	19.7
5	1.6	.85	1.1	.85	.13	1.6	1.5	.75	1.2	.96	10.5
6	1.0	.41	.57	.41	.04	.93	.88	.34	.65	.48	5.8
7	.64	.20	.29	.20	.01	.56	.52	.16	.35	.24	3.1
8	.39	.09	.15	.09	-	.33	.30	.07	.19	.12	1.8
9	.24	.05	.08	.05	-	.20	.18	.03	.10	.06	1.0
10	.15	.02	.04	.02	-	.12	.11	.02	.06	.03	0.6
11	.10	.01	.02	.01	-	.07	.06	.01	.03	.02	0.3
12	.06	.01	.01	.01	-	.04	.04	-	.02	.01	0.2
13	.03	-	.01	-	-	.03	.02	-	.01	-	0.1
p	.62	.48	.52	.48	.29	.60	.59	.46	.54	.51	
q	.38	.52	.48	.52	.71	.40	.41	.54	.46	.49	

Since the ten hail seasons do not form one uninterrupted period, it was necessary to apply the theory to each season separately. May 15 to September 15 inclusive was regarded as the season; hence N was 124 days.

(ii) Actual:

n	Actual number of runs of n hail days 1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	A
1	4	7	7	5	10	10	4	11	6	5	69
2	4	5	2	1	5	3	2	5	6	11	44
3	1	3	2	3	2	3	3	3	2	3	25
4	3	1	3	3	1	-	1	1	3	3	19
5	1	-	2	1	-	1	-	-	3	3	11
6	-	1	2	-	1	2	2	1	-	-	9
7	-	2	2	1	-	2	2	1	1	-	11
8	-	-	-	1	-	1	1	-	1	-	4
9	1	1	-	-	-	-	2	-	-	-	4
10	-	-	-	-	-	-	-	1	-	-	1
11	1	-	-	1	-	1	-	-	-	-	3
12	1	-	-	-	-	-	-	-	-	-	1
13	1	-	-	-	-	-	-	-	-	-	1

APPENDIX E

N = Number of days from May 15 to September 15 = 124

p = General probability of a hail day

q = 1 - p = General probability of a no-hail day

n = Number of consecutive hail days in a run

Year	p	q		Value of n 1	2	3	4	5	6
			Nqp^n =	29.2	17.9	11.3	7.1	4.3	2.7
1957	.62	.38	$Nqp^n - Nqp^{n+1}$ = E	11.3	6.6	4.2	2.8	1.6	1.0
			Actual Runs = A	4	4	1	3	1	0
			Nqp^n =	31.0	14.9	7.1	3.4	1.64	0.79
1958	.48	.52	$Nqp^n - Nqp^{n+1}$ = E	16.1	7.8	3.7	1.8	0.85	0.41
			Actual Runs = A	7	5	3	1	0	1
			Nqp^n =	31.0	16.1	8.4	4.4	2.3	1.18
1959	.52	.48	$Nqp^n - Nqp^{n+1}$ = E	14.9	7.7	4.0	2.1	1.1	0.57
			Actual Runs = A	7	2	2	3	2	2
			Nqp^n =	31.0	14.9	7.1	3.4	1.64	0.79
1960	.48	.52	$Nqp^n - Nqp^{n+1}$ = E	16.1	7.8	3.7	1.8	0.85	0.41
			Actual Runs = A	5	1	3	3	1	0
			Nqp^n =	25.5	7.4	2.15	0.62	0.18	.052
1961	.29	.71	$Nqp^n - Nqp^{n+1}$ = E	18.1	5.3	1.53	0.44	0.13	0.04
			Actual Runs = A	10	5	2	1	0	1
			Nqp^n =	29.8	17.9	10.7	6.4	3.9	2.32
1962	.60	.40	$Nqp^n - Nqp^{n+1}$ = E	11.9	7.2	4.3	2.5	1.6	0.93
			Actual Runs = A	10	3	3	0	1	2
			Nqp^n =	30.0	17.7	10.4	6.2	3.6	2.14
1963	.59	.41	$Nqp^n - Nqp^{n+1}$ = E	12.3	7.3	4.2	2.6	1.5	0.88
			Actual Runs = A	4	2	3	1	0	2
			Nqp^n =	30.8	14.2	6.5	3.0	1.38	0.63
1964	.46	.54	$Nqp^n - Nqp^{n+1}$ = E	16.6	7.7	3.5	1.6	0.75	0.34
			Actual Runs = A	11	5	3	1	0	1
			Nqp^n =	30.8	16.6	9.0	4.9	2.6	1.41
1965	.54	.46	$Nqp^n - Nqp^{n+1}$ = E	14.2	7.6	4.1	2.3	1.2	0.65
			Actual Runs = A	6	6	2	3	3	0
			Nqp^n =	31.0	15.2	7.6	3.8	1.92	0.96
1966	.51	.49	$Nqp^n - Nqp^{n+1}$ = E	15.8	7.6	3.8	1.9	0.96	0.48
			Actual Runs = A	5	11	3	3	3	0

Year	p	q		Value of n: 7	8	9	10	11	12	13	14
1957	.62	.38	Nqp^n =	1.67	1.03	0.64	0.40	0.25	0.15	0.09	0.06
			E =	0.64	0.39	0.24	0.15	0.10	0.06	0.03	
			A =	0	0	1	0	1	1	1	0
1958	.48	.52	Nqp^n =	0.38	0.18	0.09	0.04	0.02	0.01	0.005	0.002
			E =	0.20	0.09	0.05	0.02	0.01	0.005	0.003	
			A =	2	0	1	0	0	0	0	
1959	.52	.48	Nqp^n =	0.61	0.32	0.17	0.09	0.045	0.023	0.012	0.006
			E =	0.29	0.15	0.08	0.045	0.022	0.011	0.006	
			A =	2	0	0	0	0	0	0	
1960	.48	.52	Nqp^n =	0.38	0.18	0.09	0.04	0.02	0.01	0.005	0.002
			E =	0.20	0.09	0.05	0.02	0.01	0.005	0.003	
			A =	1	1	0	0	1	0	0	
1961	.29	.71	Nqp^n =	0.015	0.004						
			E =	0.011							
			A =	0							
1962	.60	.40	Nqp^n =	1.39	0.83	0.50	0.30	0.18	0.11	0.07	0.04
			E =	0.56	0.33	0.20	0.12	0.07	0.04	0.03	
			A =	2	1	0	0	1	0	0	
1963	.59	.41	Nqp^n =	1.26	0.74	0.44	0.26	0.15	0.09	0.05	0.03
			E =	0.52	0.30	0.18	0.11	0.06	0.04	0.02	
			A =	2	1	2	0	0	0	0	
1964	.46	.54	Nqp^n =	0.29	0.13	0.06	0.03	0.013	0.006	0.003	
			E =	0.16	0.07	0.03	0.017	0.007	0.003		
			A =	1	0	0	1	0	0		
1965	.54	.46	Nqp^n =	0.76	0.41	0.22	0.12	0.065	0.035	0.019	0.010
			E =	0.35	0.19	0.10	0.06	0.03	0.016	0.009	
			A =	1	1	0	0	0	0	0	
1966	.51	.49	Nqp^n =	0.48	0.24	0.12	0.06	0.03	0.015	0.008	0.004
			E =	0.24	0.12	0.06	0.03	0.015	0.007	0.004	
			A =	1	1	0	0	0	0	0	

APPENDIX F, PART I

PERCENTAGE FREQUENCY OF HAIL ONSET BY HOUR OF DAY

Hour of Day	1957	1958	1959	1960	1961
0023-0122	.06	-	-	.38	.96
0123-0222	.03	-	.20	.34	.77
0223-0322	-	-	.03	.17	-
0323-0422	.03	-	.03	.72	-
0423-0522	.09	-	.03	.55	-
0523-0622	.06	-	.12	.41	-
0623-722	.35	.21	.09	1.10	-
0723-0822	.12	.10	.06	4.33	-
0823-0922	1.50	.10	.18	3.95	-
0923-1022	1.39	.72	.29	1.48	-
1023-1122	3.69	1.14	1.40	.76	.19
1123-1222	7.16	3.31	3.04	2.41	1.35
1223-1322	6.99	6.83	5.00	5.98	1.98
1323-1422	9.55	11.69	7.54	7.39	5.38
1423-1522	13.92	14.37	10.66	11.76	5.00
1523-1622	18.75	10.34	12.10	11.38	6.92
1623-1722	16.13	12.00	22.20	13.58	6.73
1723-1822	8.11	13.34	16.54	13.44	8.27
1823-1922	6.04	10.34	13.29	9.42	26.54
1923-2022	3.60	9.62	3.92	3.99	20.96
2023-2122	1.77	3.72	1.08	2.68	5.19
2123-2222	.65	1.24	1.87	1.51	5.58
2223-2322	.03	.42	.26	.96	2.69
2323-0022	-	.31	.09	1.31	1.54

APPENDIX F, PART I (CONTD.)

PERCENTAGE FREQUENCY OF HAIL ONSET BY HOUR OF DAY

Hour of Day	1962	1963	1964	1965	1966
0023-0122	.47	1.24	.44	.25	.46
0123-0222	.05	.97	.08	.08	.20
0223-0322	.05	.26	.14	.03	.07
0323-0422	.05	.11	.03	.26	.13
0423-0522	-	-	-	.26	.10
0523-0622	.05	-	.03	.08	.03
0623-0722	.02	-	.03	.03	.10
0723-0822	.12	.08	.03	.06	.36
0823-0922	.07	.24	-	.03	.23
0923-1022	.05	.32	.03	.54	.33
1023-1122	.52	.42	.20	3.09	.96
1123-1222	1.20	2.47	2.95	3.65	2.01
1223-1322	3.47	4.87	8.98	4.18	3.97
1323-1422	7.21	7.52	9.20	5.99	6.09
1423-1522	12.50	13.70	8.89	7.63	11.62
1523-1622	15.35	14.49	6.97	10.49	14.29
1623-1722	14.15	14.73	11.62	18.92	12.02
1723-1822	11.02	12.86	18.87	18.55	15.08
1823-1922	6.99	8.52	15.56	9.42	17.29
1923-2022	6.22	7.37	6.00	8.14	7.71
2023-2122	8.76	4.58	3.11	6.08	3.79
2123-2222	5.56	2.00	3.42	1.73	1.94
2223-2322	4.26	2.24	1.81	1.02	.76
2323-0022	1.87	1.03	1.64	.51	.66

APPENDIX F, PART II

HOURLY PERCENTAGE FREQUENCY OF HAIL ONSET BY MONTH

Hour of Day	May	June	July	Aug.	Sept.
0023-0122	2.63	.33	.45	.36	.20
0123-0222	.88	.05	.34	.36	-
0223-0322	.88	.10	.08	.06	-
0323-0422	.44	.32	.07	.02	-
0423-0522	-	.17	.11	.02	.20
0523-0622	.22	.12	.08	.03	-
0623-0722	-	.43	.07	.06	-
0723-0822	.22	1.34	.08	.10	1.01
0823-0922	.22	1.19	.18	.74	1.21
0923-1022	.66	.92	.17	.57	.20
1023-1122	4.83	2.21	.63	.47	1.42
1123-1222	5.04	4.61	2.07	2.21	5.06
1223-1322	7.68	7.64	2.74	6.62	6.88
1323-1422	7.46	9.54	5.42	8.62	13.97
1423-1522	9.87	10.95	10.96	11.97	22.06
1523-1622	11.62	8.86	14.50	15.83	13.56
1623-1722	13.82	10.76	16.97	18.86	14.58
1723-1822	12.28	10.39	17.00	14.70	12.96
1823-1922	7.68	12.30	10.75	9.88	2.83
1923-2022	5.26	6.76	6.74	5.15	1.82
2023-2122	1.75	4.50	5.33	1.62	1.21
2123-2222	.88	2.88	2.96	1.02	.61
2223-2322	1.75	2.21	1.54	.40	-
2323-0022	3.95	1.43	.68	.34	.20

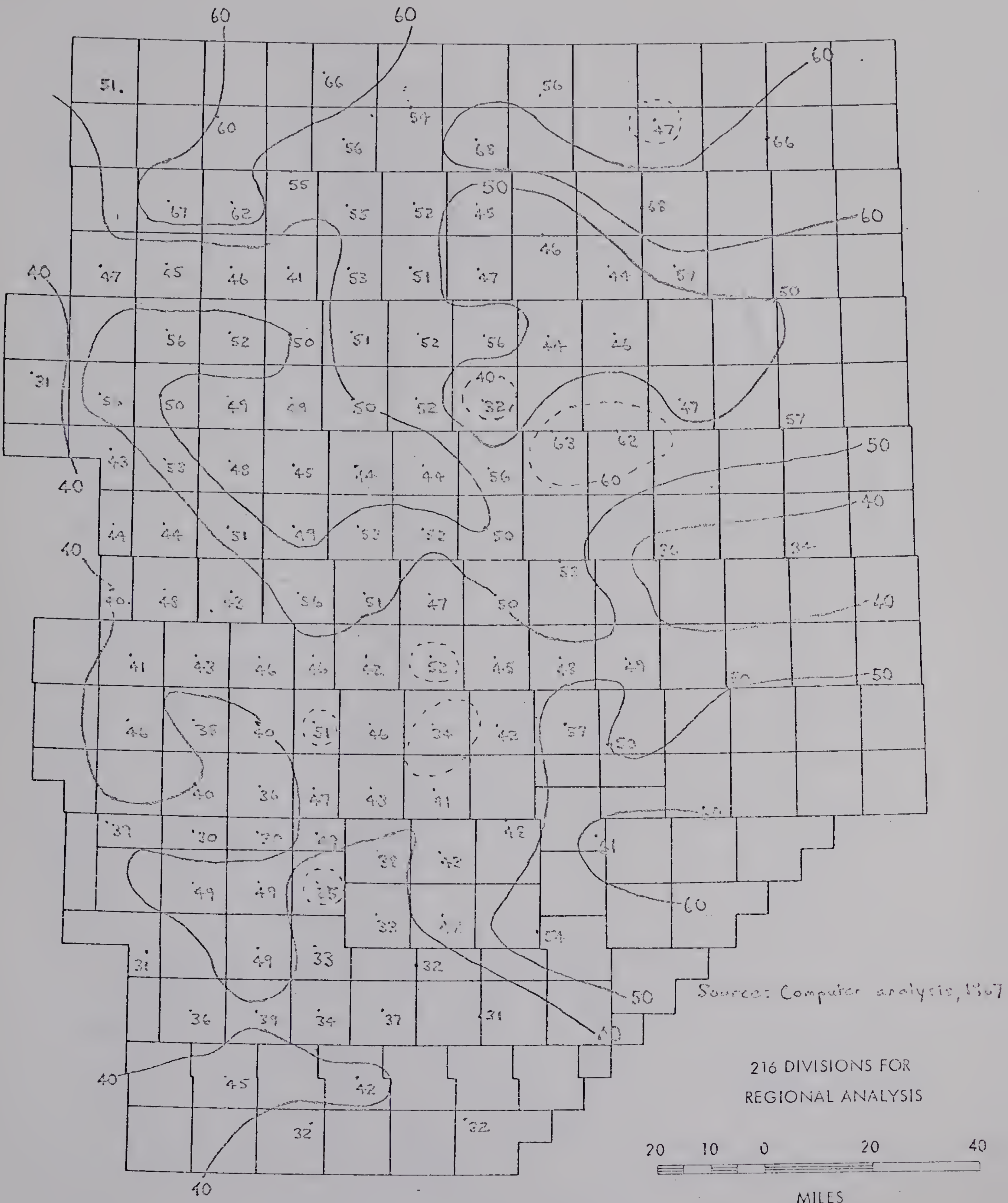
APPENDIX F, PART III

HOURLY PERCENTAGE FREQUENCY OF HAIL ONSET BY MAXIMUM SIZE OF OBSERVED HAIL

(TO NEAREST WHOLE PER CENT)

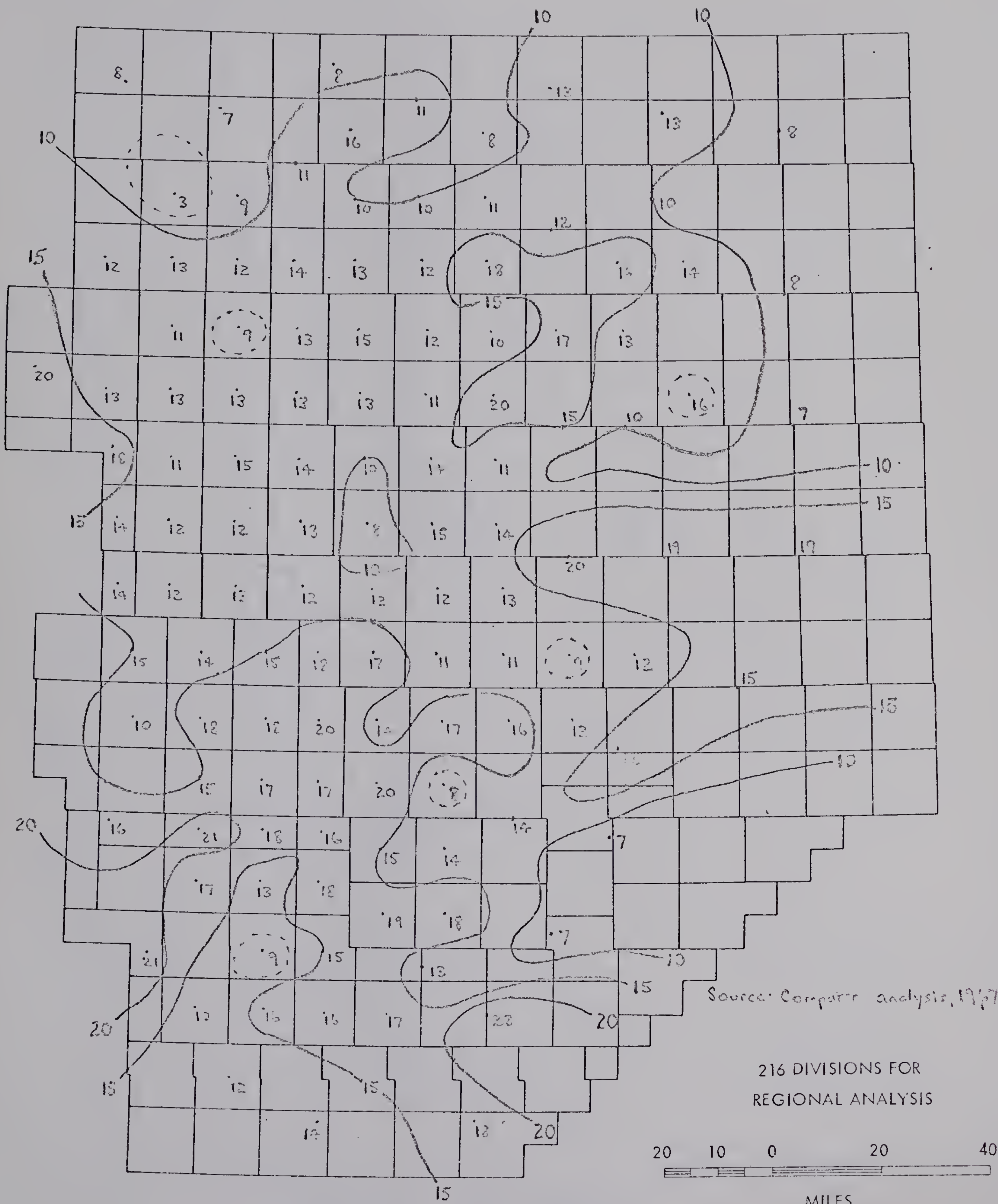
Hour of Day	Maximum Size of Observed Hail					
	Shot	Pea	Grape	Walnut	Golfball	Larger
0023-0122	-	-	-	-	-	-
0123-0222	-	-	-	-	-	-
0223-0322	-	-	-	-	-	-
0323-0422	-	-	-	-	-	-
0423-0522	-	-	-	-	-	-
0523-0622	-	-	-	-	-	-
0623-0722	-	-	-	-	-	-
0723-0822	-	-	-	-	-	-
0823-0922	-	-	-	-	1	-
0923-1022	-	-	-	-	-	-
1023-1122	2	1	-	-	-	-
1123-1222	6	4	2	-	1	-
1223-1322	9	6	4	4	3	2
1323-1422	10	9	7	6	3	1
1423-1522	13	12	11	8	8	4
1523-1622	13	12	12	13	19	26
1623-1722	12	14	15	18	26	35
1723-1822	12	13	15	17	16	15
1823-1922	10	10	11	12	13	9
1923-2022	5	6	7	8	5	4
2023-2122	2	4	5	5	3	5
2123-2222	3	4	3	3	-	-
2223-2322	-	1	-	1	1	-
2323-0022	-	-	-	-	-	-

APPENDIX G



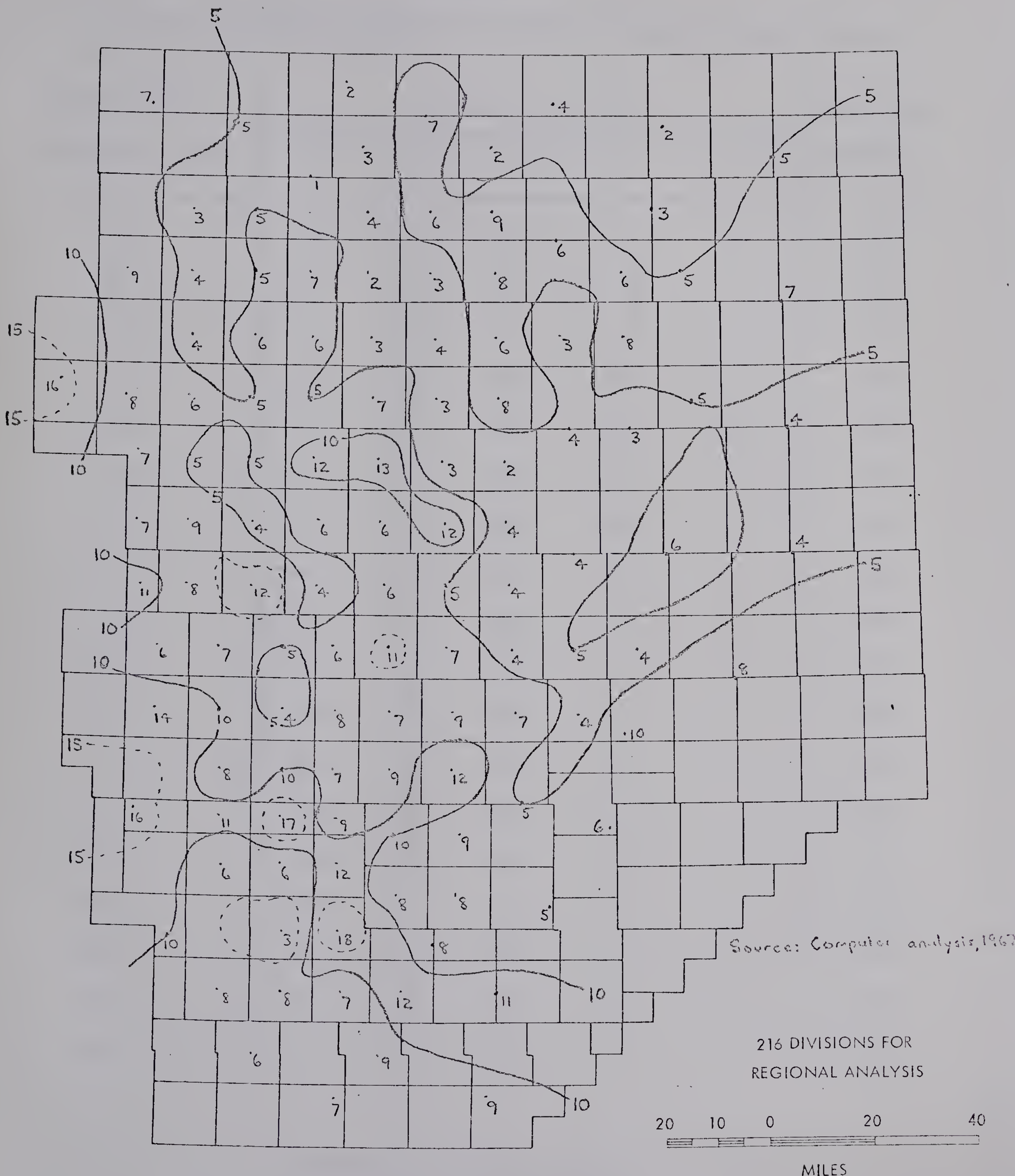
APPENDIX G, MAP 1

PERCENTAGE OF REPORTS WITH DURATION OF HAIL 0-6 MINUTES



APPENDIX G, MAP 2

PERCENTAGE OF REPORTS WITH DURATION OF HAIL 13-18 MINUTES



APPENDIX G, MAP 3

PERCENTAGE OF REPORTS WITH DURATION 25 MINUTES AND LONGER

APPENDIX H

DURATION PERCENTAGE FREQUENCIES BY DISTANCE FROM THE ROCKY MOUNTAINS

Approx. Mean Distance (mls.)	Duration in minutes 0-6	7-12	13-18	19-24	25 & over	Total Known Durations
33	34	30	10	9	16	105
40	41	29	15	8	7	221
45	43	29	14	9	6	340
50	39	28	17	10	6	387
55	39	27	14	10	10	444
60	39	26	16	10	9	719
65	41	26	14	10	9	963
70	33	27	17	10	12	1087
75	40	27	15	9	7	1325
80	43	24	15	9	8	1442
85	45	25	14	7	9	1519
90	47	23	16	8	7	1476
95	53	25	11	6	5	1574
100	48	26	14	6	7	1339
105	48	27	14	5	6	1544
110	48	25	14	7	6	1301
115	47	26	11	8	7	1532
120	47	27	11	6	7	1694

Concluded on following page.

Approx. Mean Distance (mls.)	Duration in minutes 0-6	7-12	13-18	19-24	25 & over	Total Known Durations
125	50	24	13	6	7	1371
130	50	26	12	6	6	1289
135	51	28	13	5	3	1210
140	54	24	12	7	3	917
145	52	25	13	6	4	800
150	53	24	13	6	4	672
155	53	23	15	5	4	425
160	51	24	13	6	7	432
165	47	25	14	8	6	406
170	51	26	12	6	5	354
175	52	27	11	5	5	302
180	49	26	15	6	5	314
185	55	21	13	4	7	189
190	55	22	11	8	4	180
195	56	25	8	7	4	165
200	49	27	12	8	5	107
205	47	32	10	6	4	79
218	61	22	8	5	4	142

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APPENDIX J

MAXIMUM OBSERVED HAIL SIZE DATA

(i) Variation by Year

NUMBERS OF REPORTS

Year	Maximum Size Observed						Total, size specified
	Shot	Pea	Grape	Walnut	Golfball	Larger	
1957	226	1277	1027	404	237	50	3221
1958	112	484	259	50	13	0	918
1959	310	1415	1065	324	178	45	3337
1960	181	820	960	440	318	151	2870
1961	35	240	259	86	22	1	643*
1962	270	1564	1538	560	164	35	4131
1963	410	1498	1356	439	133	44	3880
1964	344	1255	1218	541	183	22	3563
1965	464	1466	1215	475	98	23	3741
1966	411	1348	1018	276	47	4	3104
Total	2763	11367	9915	3595	1393	375	29408
Mean	276	1137	992	360	139	38	2941

* This total is rather larger than the total of reports for 1961 obtained from the computer, perhaps due to the inclusion of some reports from trial surveys run in 1961.

PERCENTAGES OF TOTAL WITH MAXIMUM SIZE SPECIFIED

Year	Maximum Size Observed					
	Shot	Pea	Grape	Walnut	Golfball	Larger
1957	7.0	39.6	31.9	12.5	7.4	1.6
1958	12.2	52.7	28.2	5.4	1.4	0.0
1959	9.3	42.4	31.9	9.7	5.3	1.4
1960	6.3	28.6	33.4	15.3	11.1	5.3
1961	5.4	37.2	40.3	13.4	3.4	0.2
1962	6.5	37.9	37.2	13.6	4.0	0.8
1963	10.6	38.6	34.9	11.3	3.4	1.1
1964	9.7	35.2	34.2	15.2	5.1	0.6
1965	12.4	39.2	32.5	12.7	2.6	0.6
1966	13.2	43.4	32.8	8.9	1.5	0.1
Overall	9.4	38.7	33.7	12.2	4.7	1.3

(ii) Individual Months

(a) NUMBERS OF REPORTS

1957

Month	Maximum Size Observed						Total, size specified
	Shot	Pea	Grape	Walnut	Golfball	Larger	
June	93	540	329	72	7	1	1042
July	85	471	462	230	193	41	1482
August	23	192	217	100	37	8	577
Sept.	25	74	19	2	0	0	120
Totals	226	1277	1027	404	237	50	3221

1958

Month	Maximum Size Observed: Shot	Pea	Grape	Walnut	Golfball	Larger	Total, size specified
June	54	190	72	7	3	0	326
July	33	160	81	12	0	0	286
August	19	96	80	29	10	0	234
Sept.	6	38	26	2	0	0	72
Totals	112	484	259	50	13	0	918

1959

May	1	4	1	0	0	0	6
June	175	679	412	67	6	0	1339
July	85	459	313	21	10	0	888
August	46	252	322	236	162	45	1063
Sept.	3	21	17	0	0	0	41
Totals	310	1415	1065	324	178	45	3337

1960

June	97	476	415	148	81	10	1227
July	41	192	447	278	235	140	1333
August	43	152	98	14	2	1	310
Sept.	0	0	0	0	0	0	0
Totals	181	820	960	440	318	151	2870

1961

Month	Maximum Size Observed						Total, size
	Shot	Pea	Grape	Walnut	Golfball	Larger	specified
May	3	10	9	1	0	0	23
June	19	146	202	79	22	0	468
July	7	66	46	6	0	0	125
August	3	3	0	0	0	1	7
Sept.	3	15	2	0	0	0	20
Totals	35	240	259	86	22	1	643

1962

May	8	37	18	5	0	0	68
June	92	688	770	273	50	2	1875
July	121	613	575	227	105	32	1673
August	42	208	167	51	9	1	478
Sept.	7	18	8	4	0	0	37
Totals	270	1564	1538	560	164	35	4131

1963

May	7	15	3	0	0	0	25
June	116	398	275	39	8	0	836
July	172	643	610	231	61	17	1734
August	113	435	464	169	64	27	1272
Sept.	2	7	4	0	0	0	13
Totals	410	1498	1356	439	133	44	3880

Month	Maximum Size Observed						Total, size specified
	Shot	Pea	Grape	Walnut	Golfball	Larger	
1964							
May	3	3	2	0	1	0	9
June	141	416	315	150	58	2	1082
July	124	597	656	225	80	12	1694
August	69	232	245	166	44	8	764
Sept.	7	7	0	0	0	0	14
Totals	344	1255	1218	541	183	22	3563
1965							
May	13	94	89	18	0	0	214
June	156	380	126	10	0	0	672
July	165	614	614	317	71	14	1795
August	92	330	364	125	26	9	946
Sept.	38	48	22	5	1	0	114
Totals	464	1466	1215	475	98	23	3741
1966							
May	16	54	44	9	2	0	125
June	169	581	270	38	2	0	1060
July	108	477	587	191	33	3	1399
August	111	219	112	38	10	1	491
Sept.	7	17	5	0	0	0	29
Totals	411	1348	1018	276	47	4	3104

(b) PERCENTAGES OF TOTAL WITH SIZE SPECIFIED

1957

Period	Shot	Pea	Grape	Walnut	Golfball	Larger
	Maximum Size Observed					
June	9.0	51.8	31.6	6.9	0.7	0.1
July	5.7	31.8	31.2	15.5	13.0	2.8
August	4.0	33.3	37.6	17.3	6.4	1.4
Sept.	20.8	61.7	15.8	1.7	-	-
Whole year	7.0	39.6	31.9	12.5	7.4	1.6

1958

Period	Shot	Pea	Grape	Walnut	Golfball	Larger
June	16.6	58.3	22.1	2.1	0.9	-
July	11.5	56.0	28.3	4.2	-	-
August	8.1	41.0	34.2	12.4	4.3	-
Sept.	8.3	52.8	36.1	2.8	-	-
Whole year	12.2	52.7	28.2	5.4	1.4	-

1959

Period	Shot	Pea	Grape	Walnut	Golfball	Larger
May	16.7	66.6	16.7	-	-	-
June	13.1	50.7	30.8	5.0	0.4	-
July	9.6	51.7	35.3	2.3	1.1	-
August	4.3	23.7	30.3	22.2	15.3	4.2
Sept.	7.3	51.2	41.5	-	-	-
Whole year	9.3	42.4	31.9	9.7	5.3	1.4

1960

Period	Maximum Size Observed Shot	Pea	Grape	Walnut	Golfball	Larger
June	7.9	38.8	33.8	12.1	6.6	0.8
July	3.1	14.4	33.5	20.9	17.6	10.5
August	13.9	49.0	31.6	4.5	0.6	0.3
Sept.	-	-	-	-	-	-
Whole year	6.3	28.6	33.4	15.3	11.1	5.3

1961

Period	Shot	Pea	Grape	Walnut	Golfball	Larger
May	13.0	43.5	39.1	4.4	-	-
June	4.1	31.2	43.2	16.9	4.7	-
July	5.6	52.8	36.8	4.8	-	-
August	42.9	42.9	-	-	-	14.2
Sept.	15.0	75.0	10.0	-	-	-
Whole year	5.4	37.2	40.3	13.4	3.4	0.2

1962

Period	Shot	Pea	Grape	Walnut	Golfball	Larger
May	11.8	54.4	26.5	7.3	-	-
June	4.9	36.7	41.1	14.6	2.7	0.1
July	7.2	36.6	34.4	13.6	6.3	1.9
August	8.8	43.3	34.9	10.8	1.9	0.2
Sept.	18.9	48.6	21.6	10.8	-	-
Whole year	6.5	37.9	37.2	13.6	4.0	0.8

1963

Period	Maximum Size Observed Shot	Pea	Grape	Walnut	Golfball	Larger
May	28.0	60.0	12.0	-	-	-
June	13.9	47.6	32.9	4.7	0.9	-
July	9.9	37.1	35.2	13.3	3.5	1.0
August	8.9	34.2	36.5	13.4	5.0	2.1
Sept.	15.4	53.8	30.8	-	-	-
Whole year	10.6	38.6	34.9	11.3	3.4	1.1

1964

Period	Shot	Pea	Grape	Walnut	Golfball	Larger
May	33.3	33.3	22.2	-	11.1	-
June	13.0	38.4	29.1	13.9	5.4	0.2
July	7.3	35.2	38.7	13.3	4.7	0.7
August	9.0	30.4	32.1	21.7	5.8	1.0
Sept.	50.0	50.0	-	-	-	-
Whole year	9.7	35.2	34.2	15.2	5.1	0.6

1965

Period	Shot	Pea	Grape	Walnut	Golfball	Larger
May	6.1	43.9	41.6	8.4	-	-
June	23.2	56.5	18.8	1.5	-	-
July	9.2	34.2	34.2	17.7	4.0	0.8
August	9.7	34.9	38.5	13.2	2.7	1.0
Sept.	33.3	42.1	19.3	4.3	0.9	-
Whole year	12.4	39.2	32.5	12.7	2.6	0.6

1966

Period	Maximum Size Observed Shot	Pea	Grape	Walnut	Golfball	Larger
May	12.8	43.2	35.2	7.2	1.6	-
June	15.9	54.8	25.5	3.6	0.2	-
July	7.7	34.1	42.0	13.7	2.4	0.2
August	22.6	44.6	22.8	7.8	2.0	0.2
Sept.	24.1	58.6	17.2	-	-	-
Whole year	13.2	43.4	32.8	8.9	1.5	0.1